THE EFFECTS OF THE EQUITABLE CANAL WATER ALLOCATION MODEL SCHEDULING ON CROPS AND SOILS UNDER THE WARABANDI WATER MANAGEMENT SYSTEM:

A CASE STUDY OF THE HAKRA BRANCH CANAL COMMAND AREA OF THE PUNJAB PROVINCE PAKISTAN

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requirements for the Degree in

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ABSTRACT

Agriculture is the mainstay of the economy of Pakistan and accounts for 21% of the Gross Domestic Product (GDP) and 80% of the export revenue. It also employs about 48% of the labour force in the country. Punjab province is considered to be the bread basket of Pakistan by virtual of the crop produces as it accounts for 83% cotton, 80% wheat, 97% rice , 63% sugarcane and 51% maize, all of which are grown under irrigation. There are a number of constraints that the irrigation system faces that include design constraints, water availability constraints, conveyance losses, soil salinity, sodicity, sedimentation and financial crunches. Most of these constraints would require the government to rethink how the irrigation system works in order to overcome them. For example, to overcome the design constraints, land reform might be necessary (not very popular), massive investment would be required to upgrade the conveyance system to reduce system losses while due to increase in population and climate variability, water availability can only get worse.

The easier way for the time being is to try and ensure equitable distribution of the water available among the farming community through development of better irrigation and service interruption scheduling techniques. The Equitable Canal Water Allocation (ECWA) model has been developed to ensure equitable water distribution by proper scheduling of service interruption. Several scheduling scenarios have been developed but their effect on crops and soils is unknown.

AquaCrop, a crop water productivity model, has been used to investigate the effects of these scheduling scenario as it is cheaper and faster when compared to practical implementation in the field. Three scheduling scenarios that have been investigated are: Punjab Irrigation Department (PID) Scenario (status quo), Scenario A (most inequitable) and Scenario I (most equitable). These scenarios have been applied to cotton and wheat across different planting dates as practiced on the ground in order to determine their effects on achievable yield, conjunctive water use, root zone depletion and salinity build in the soil profile.

A comparison between on achievable yield, conjunctive water use, root zone depletion and salinity build has shown that there is minimal variation between PID scenarios and both Scenario A and I. This could be interpreted to mean that it is possible to enhance equity of water delivery without necessarily affecting on achievable yield, conjunctive water use, root zone depletion and salinity build. It is worth noting that planting early in the season has been shown to yield more than planting late in the season, but other factors (labour, machinery and certified seed) might prevent early planting.

GLOSSARY

Abiana	Water charges.
Absolute optimum water requirement	Water requirement by crops as determined agronomically.
Bandi	Fixed.
Command area	Area served by water course or a distributary or a main canal.
Culturable command area	Percentage of command area that can be cultivated.
Gini Index	Measure of inequality.
Kharif	Summer time (mid-April top mid-October)
Rabi	Winter time (mid- October to mid-April
Rauni	Pre-soaking irrigation
Reduced Distance	Distance from the headworks or secondary offtake structure to the inlet of canal in question
Mogha	Ungated fixed size outlet that allows water to flow into a watercourse from a canal.
Target allocation	Water supplied to the crops as determined by irrigation scheduling.
Tubewell	Well used for irrigation.
Wahr	Turns.
Warabandi	List of rotational times/turns when each farmer in a watercourse gets his water share.
Water allowance	Outlet capacity authorised per 100 acres of culturable command area.

LIST OF ABBREVIATIONS AND NOTATIONS

APSIM	Agricultural Production Systems Simulator
ASCE	American Society of Civil Engineers
B	Dry biomass (ton/ha)
C_d	Denominator constant that changes with reference crop type and calculation time step
C_n	Numerator constant dependent on reference crop type and calculation time step
CC	Green canopy cover (%)
CC*	Green canopy cover adjusted for micro-advection (%)
CR	Capillary rise
CROPSYST	Crop Systems Model
d	Willmott's index of agreement
D_r	Root zone depletion (mm)
DSSAT	Decision Support System for Agrotechnology Transfer
E	Soil evaporation (mm/unit time)
e_a	Actual vapour pressure
e_s	Saturation vapour pressure
ECe	Electrical conductivity of saturated soil paste extract (dS/m)
ECWA	Equitable canal water allocation
EF	Nash-Sutcliffe model efficiency coefficient
ET	Evapotranspiration
ET_O	Crop reference evapotranspiration
ET_{os}	Short reference crop evapotranspiration
ET_{rs}	Tall reference crop evapotranspiration
ET_{sz}	Standardized reference crop evapotranspiration
FC	Field capacity
G	Soil heat flux density at the soil surface
g_s	Stomatal conductance (m/s)
GDD	Growing degree days (˚C d)
GOW	Groundwater observation well

GW	Groundwater
HBC	Hakra Branch Canal
HI	Harvest Index (percent)
I	Irrigation
IWMI	International Water Management Institute
K_{cbx}	Crop coefficient when CC is fully developed
K_{sat}	Hydraulic conductivity at saturation
NRMSE	Normalised room mean square error
P	Rainfall
PID	Punjab Irrigation Department
PWP	Permanent wilting point
R^2	Coefficient of determination
RH	Relative humidity
R_n	Calculated net radiation at the crop surface
RRMSE	Relative Root Mean Square Error
SF	Surface flows
STICS	Simulateur Multidisciplinaire pour les Cultures Standard
SWAP	Soil-Water-Atmosphere-Plant
SWAT	Soil and Water Assessment Tool
τ	Drainage coefficient
T_{avg}	Average air temperature (˚C).
T_{base}	Base temperature (no crop development occurs) (˚C)
$T_{max}=T_x$	Daily maximum air temperature (˚C)
$T_{min}= T_n$	Daily minimum air temperature (˚C
T_r	Crop transpiration (mm/unit time)
TAW	Total available soil water (mm/m)
u_2	Wind speed measured at 2 m above ground surface (m/s)
USDA	United State Department of Agriculture
WP	Crop biomass water productivity (kg/m^3)
$WP_{lint/ET}$	WP as the ratio of lint of cotton to evapotranspiration (kg/m^3)
$WP_{Y/ET}$	WP as a ratio of yield as dry matter to evapotranspiration (kg/m^3)

WP^*	WP normalised for ET_O and air CO_2 concentration (ton/ha or kg/ha)
W_r	Water stored in the root expressed as an equivalent depth (mm)
W_{rfc}	Soil water content of the root zone at field capacity
WaSiM	Water Flow Balance Simulation Model
γ	Psychrometric constant
Y	Yield (ton/ha or kg/ha)
Δ	Slope of the saturation vapour pressure-temperature curve
Z_e	Effective rooting depth
Z_x	Maximum rooting depth
Θ_{sat}	Soil water content at saturation (m^3/m^3)

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CHAPTER 1: INTRODUCTION

1.1. Pakistan overview

Pakistan, also known as the Islamic Republic of Pakistan, is a country located in South Asia and is bound by China to the north, India to the east, Iran and Afghanistan to the west and the Arabia Sea to the south (Figure 1-1). The country is located between latitudes 22.5˚ and 35˚ north and longitudes 60˚ and 75˚ east. It has diverse topographical features ranging from mountain ranges in the north to the coastal plains in the south. The climate therefore varies from subtropical arid and semi-arid to temperate sub humid in Sindh and Punjab provinces to alpine in the mountainous highlands in the north. The climate of the centre and south of the country (Punjab, Sind and Baluchistan) is characterised by two seasons, Kharif and Rabi. Kharif is characterised by hot and dry summers with temperatures reaching 40˚- 45˚C. Summer monsoon rainfall also occurs in Kharif and varies greatly from north to south. Rabi is characterised by cool winters with temperatures up to 25˚C. Alpine climatic conditions are experienced in the north due to the mountain ranges and are characterised by long, cold and snowy winters with short and mild summers. The climate of the southern coastal strip (Indus Delta and cities such as Karachi and the whole of Markan coast) is characterised by sea breeze all the year round which lower the range of daily temperature (FAO, 2011; Fowler & Archer, 2005; Naz, 2010).

The country receives an average annual rainfall of about 300 mm per year, with the northern valley floors receiving between 100 mm and 200 mm, 600 mm at altitude 4,400 m and about 1,500 - 2,500 mm at altitude 5,500 m and higher (Fowler & Archer, 2005). Most of the agricultural production takes place in areas that receive annual rainfall of 648 mm and annual evapotranspiration of about 2000mm (Kijne & Kuper, 1995). The rainfall received in these areas is always exceeded by the potential evapotranspiration of most crops (Meerbach, 1997). The deficit is offset by extensive and intensive irrigation by either gravity irrigation, tubewell irrigation or both.

The country has a total area of 796,096 km^2 (Pakistan Bureau of Statistics, 1998) and an approximate population of 185.1 million (World Population Review, 2014). This gives a population density of 232 inhabitants /$km^{2.}$ About 54% of the population lives in Punjab province, along the main rivers of Indus Plain (Population Welfare Department, 2013). According to Agriculture Department (2014), agriculture provides 21% of the gross domestic product (GDP) and 80% of the total export earnings when grouped together with other agro-based products. The sector also employs about 48% of the labour force.

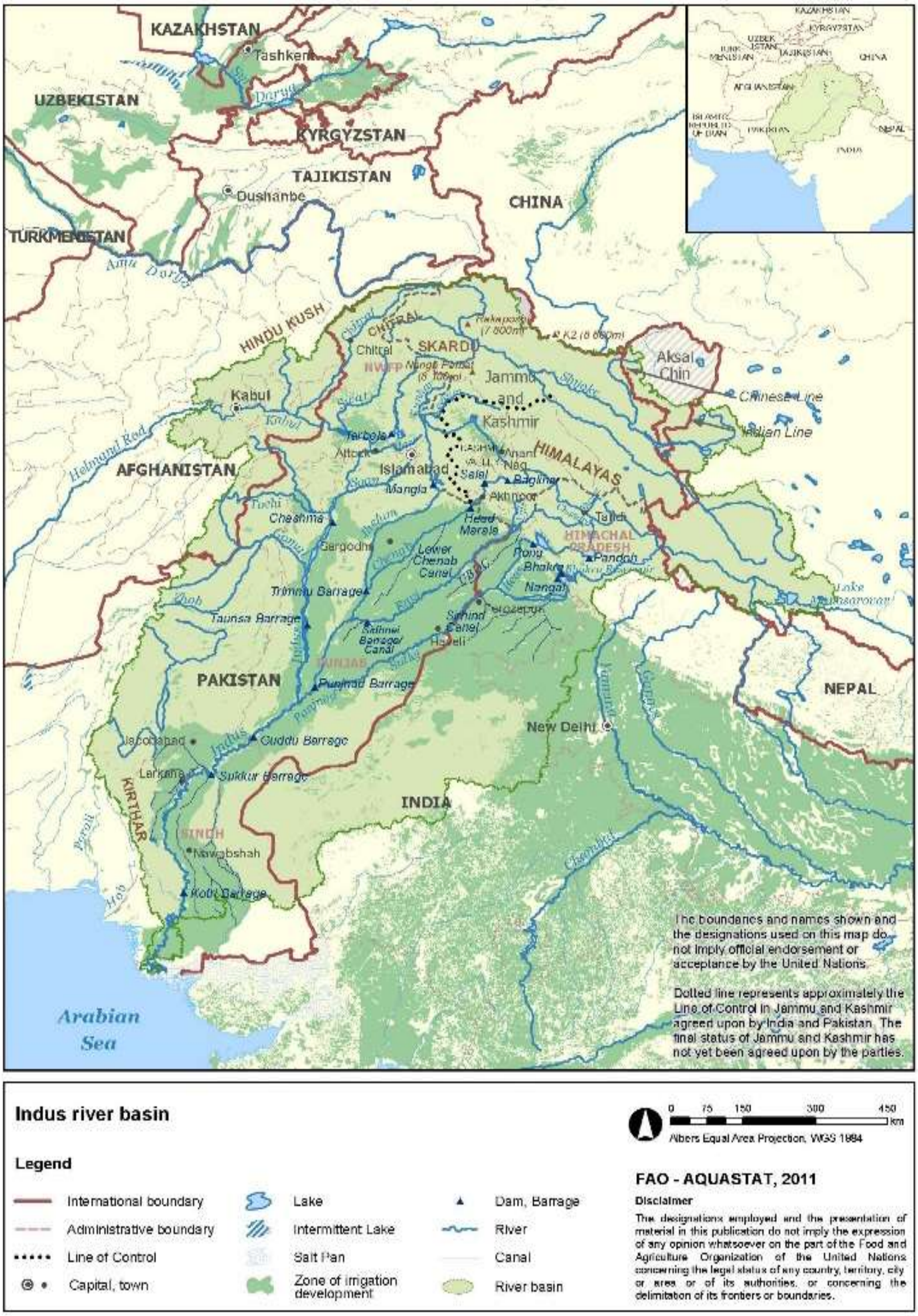


Figure 1-1 Location map of Pakistan, Indus river and its tributaries (FAO, 2011)

1.2. Indus Basin Irrigation System

The Indus Basin Irrigation System (IBIS) is recognised as the world's largest integrated irrigation system (Sohag & Mahessar, 2004) (Figure 1-2).Water that flows in this river system is composed of glacier melt, snowmelt, rainfall and runoff. The Upper Indus river basin has the largest area of perennial glacial ice (22,000 km^2) outside of the polar regions but during winter, the snow covers greater area than 22,000km^2 (FAO, 2011). The glaciers are located on the Karakorum-Hindukush-Himalaya (KHH) ranges and provide perennial supply to the Indus River and its major tributaries: Jhelum, Chenab, Ravi and Sutlej. 70% of the water in these rivers arise from glacial and snow melt while the remaining 30% comes from the monsoon rainfall (FAO, 2011).

The agricultural centre of Pakistan is situated in the Indus Plain along the five major rivers and is called Punjab (meaning land of five rivers) (Meerbach, 1997). Irrigated agriculture in this plain has been attributed to be the driving force behind the 4,000 year old Indus civilization (FAO, 2011). This was mainly carried out using a network of inundation canals, which were only able to deliver water during high river flow. Canal irrigation was introduced in 1859 by the British rulers when they discovered that they could use the perennial rivers to irrigate the fertile Indus Plain (FAO, 2011; Malhotra, 1982).The initial canals that were constructed concentrated on using water from individual rivers but by early 1900s, there was general realisation that water resources from the individual rivers was not proportionate to the potential irrigable land (FAO, 2011). Some rivers could not fully serve the area allocated while others had surplus water which led to construction of water reservoirs, headworks, link canals and main canals to supply water to the Indus Plain.

In 1947, the British colony of India was divided into two countries, India and Pakistan, thereby dividing Punjab province into East Punjab (India) and West Punjab (Pakistan). The irrigation system, as a consequence, was also divided into two without any regard to irrigation boundaries. The headworks remained upstream in East Punjab while the dependent canals were downstream in West Punjab. Continuity of flow into Pakistan was enabled through temporary agreements between the two countries. The agreements expired on 31 March 1948 and on 1 April 1948, India stopped water flowing into Pakistan (Asif, 2013).

This led to an international water dispute. The closure created a water scarcity which endangered the winter crop nearing maturity and the summer crop which was to be sown after harvesting the winter crop. Loss of two crops in a year would have a severe impacts on the Pakistan economy. This lead to the signing of Inter-Dominion Agreement on 4 May 1948 which enabled Pakistan to draw water from East Punjab and laid down conditions for continued bilateral talks.

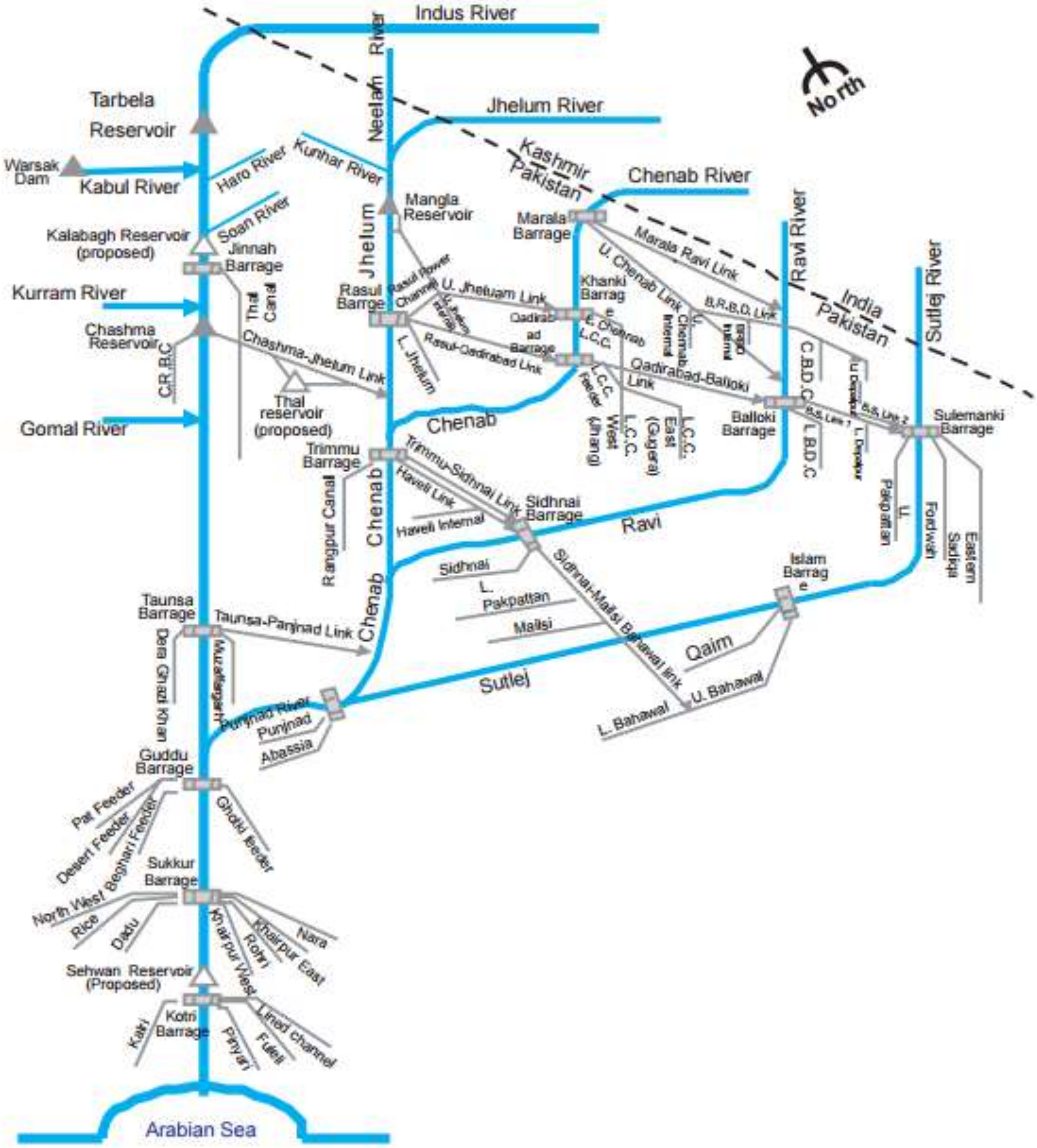


Figure 1-2 Indus Basin Irrigation System (FAO, 2015)

The dispute was finally resolved when the two countries signed and enforced the Indus Water Treaty in 1960 under the guidance of the World Bank (FAO, 2011). Pakistan gained rights on waters of Indus, Jhelum and Chenab rivers while India received the rights for the use of waters in Sutlej and Ravi rivers.

As a result of the Indus Water Treaty, the Indus Basin Project (IBP) was born (FAO, 2011). IBP had two main tasks; construction of two reservoirs on Jhelum (Mangla) and Indus (Tarbela) to lessen the effect of diverting water to East Punjab and to increase agricultural production. Chashma dam was later added to the IBP to regulate the flow in Indus River. Construction of the reservoirs was carried out in conjunction with the accompanying water diversion and delivery infrastructure (barrages, siphons and link canals).

Pakistan's irrigation system is based on classical design approach consisting of two major components: **the main system (primary and secondary canals)** and **the tertiary system** (Figure 1-3). Headworks, link canals, main canals and/or branch canals and cross regulators, secondary canals (distributaries, minors and sub-minors), secondary cross regulators and off take structures make up the main system. The tertiary system is made up of one tertiary outlet structure, commonly referred to as a mogha, and the dependent tertiary canals (watercourses). Farm intake structures at tertiary units are called nakkha which feed the field watercourses (Bhutta, 1990; Malhotra, 1982; Meerbach, 1997).

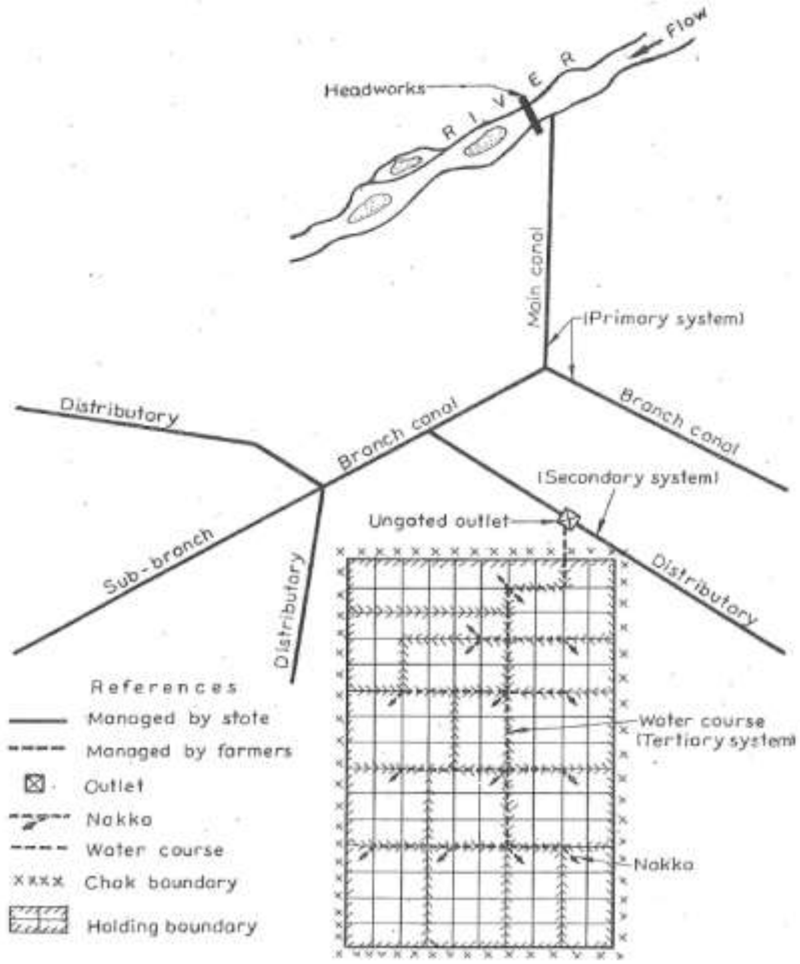


Figure 1-3 **Irrigation infrastructure layout (Malhotra, 1982)**

The Indus Basin System has three reservoirs (Mangla, Tarbela and Chashma dams), 23 barrages/headworks/siphons, 12 inter-river link canals and 46 canals commanding an area of 14.87 million ha (2008,(FAO, 2011)) and serves about 90,000 tertiary units. The total length of main canals (branches), secondary canals (distributaries, minor and sub-minors) is 60,800km while the communal water courses, farm channels and field diches cover approximately 1.6 million km (FAO, 2011; Meerbach, 1997). Water that flows into the farms is distributed by over 107,000 watercourses which are fed through outlets from distributaries and minors (Bhutta, 1990; Malhotra, 1982; Meerbach, 1997).

According to FAO (2011), 95 % of irrigated land in Pakistan is located in the Indus river basin. As of 2008, 19.99 million ha were estimated to be equipped for irrigation. About 14.87 million ha lies within IBIS while 4.4millon ha lies outside the basin. The Punjab province accounts for 69% of the total cropped area in Pakistan. The major crops cultivated in the basin depend on the season of the year and include:

a) Wheat (Rabi);
b) Cotton, rice and oil seeds (Kharif);
c) Cereals (maize, sorghum and millet) (Rabi – Kharif overlap between February and August);
d) Sugarcane and all fruits (year round).

The province contributes about 83% of cotton, 80% of wheat, 97% of rice, 63% of sugarcane and 51% of maize of the nationals food produced in the country (Agriculture Department, 2014). It also makes Pakistan the fourth largest cotton producer in the world and the largest cotton yarn exporter (Banuri, 1998; Cotton Incorporated, 2015; The Statistical Portal, 2015b).

1.3. Irrigation principles in Pakistan

When irrigation in the Indus basin was being canalised by the British rulers, they discovered that water the supply from the five rivers was highly variable between seasons and years (Malhotra, 1982; A. S. Qureshi & Fatima, 2012). They proposed to adopt one of the two options;

a) Design the system in such a way as to restrict the area under irrigation to be fully irrigated at times when the supply was at its lowest. This would lead to maximum production per unit of land under irrigation but not per unit of water available.
b) Design a system such that it covers a larger area that could be irrigated with the lowest available water thereby creating perpetual scarcity conditions. This would lead to maximum production per unit of water available and not per unit of land covered and would provide insurance against famine as there was likelihood of farmers getting yields from their land albeit not the optimum yield. It was also considered to have a greater social appeal.

Option two was selected for implementation. The principles of this option are to offer **protective irrigation** (spreading available water to an area as large as possible) and allow **equitable distribution** of canal water (designing the system in such a way as to divide flow into fixed ratio especially at the outlet structures when distributing to the tertiary units) (Malhotra, 1982; Meerbach, 1997). Jurriëns et al. (1996) indicate that protective irrigation has specific technical, management and socio-economic characteristics as shown in Table 1-1.

Table 1-1 Characteristics of protective irrigation

Technical	Management	Socio-economic
Low cropping intensity	Planned water scarcity	Poverty and famine eradication as the main objectives
Low water supply	Constant canal flows	Benefits spread over a large area
Low water demanding crops	Controlled cropping pattern	Crop yields mainly subsistence
Supply oriented water control		Family labour
Optimization of unit of water and not unit of land		

This method of water provision is commonly referred to as Warabandi which means turns (wahr) which are fixed (bandi) and is commonly practiced in Pakistan and India (Bandaragoda & ur Rehman, 1995; Malhotra, 1982). Water is supplied to the farmers in turns which are fixed according to a time roster, specifying the day, time and duration for each farmer. Duration of supply is governed by the size of land held by the farmer, an allowance is added to compensate for conveyance losses but none is made for seepage losses (Laghari, 2009). Water provision and distribution up to the mogha is the responsibility of the government while the farmers take care of on-farm structures and distribution.

The Warabandi concept, although legalised by the British rulers in the Northern India Canal Drainage Act of 1873 (Malhotra, 1982), is seen to reflect local traditions in water distribution. It may have been adopted from pre-existing cultural practices where the ruler had the responsibility of social welfare while the locals participated in resource management while complying with the laws of the administrators (Bandaragoda & ur Rehman, 1995).

According to Malhotra (1982), Warabandi schedules are made in such a way as to provide a certain flow rate called water allowance to each unit of culturable command area (CCA). The watercourses are designed to have a water allowance of 0.17 L/s/ha in India (Malhotra, 1982) while it is about 0.28 L/s/ha in Punjab Pakistan (Bandaragoda & ur Rehman, 1995). The actual range vary between 0.2 and 0.3 L/s/ha. This implies that even when the farmer is receiving the maximum allowance of 0.3 L/s/ha, equivalent to 2.6mm/day of irrigation, it is impossible to meet evapotranspiration of 3 mm/ day in the coldest month (De Vries & Anwar, 2015).

When a canal is operating on a Warabandi interval (roster), it is usually flowing at full capacity. This is done to ensure that (Anwar & Haq, 2013):

a) Water in the canal is at the required height to command the neighbouring field;
b) Outlets along a distributary releases discharges into moghas nearly equal to the rated discharge of the outlet so as to minimize inequality;
c) To allow water achieve designed non-silting, non-scoring velocity to avoid silting and scoring.

While the Warabandi system is based on equity in water provision, Bandaragoda & ur Rehman (1995) have shown that in practice, this has not been the case. Their study indicated that inequity in the system is caused by:

a) Variability in design related water allowances (distributaries have varying sets of water allowance);
b) Variable flow at distributary head;
c) Variable flow at watercourse head;
d) Variable flow within the watercourse.

This inequity has led farmers to be innovative. They use several methods that are a clear deviation from the traditional Warabandi schedule. Examples include merging 2-3 turns by family members or lending and borrowing of turns and substitution of turns depending on the size of farms (small farms giver large farms 2-3 turns for better coverage and the large farms in turn give the small farms in one turn to their satisfaction). Selling of water rights used to be a common practice but it is rare these days (Bandaragoda & ur Rehman, 1995).

1.4. Problems in the irrigation system

1.4.1. Design constraints

The water allocation of the canals in the Warabandi system deliberately introduces water scarcity in the system. The objective was to spread water as far as possible and command as much land as possible. Ul Haq (1998) states that the system was designed to handle a cropping intensity of between 60- 80% but due to changes in population, economic, social, agricultural factors and canal operations, the cropping intensity has changed. As a result, the design capacities and considerations which were applied at the time during system construction are no longer relevant. It is estimated that the cropping intensity is over 122% (Sufi, 2011). The shift in the type of crops grown (from food crops to high yielding cash crops) has resulted to the need for maximising irrigation water supply leading to increased demand in the amount of water required that was not foreseen during system design.

Bhutta (1990) found some canals with discharges of less than 75% of the design discharge for between 102 and 188 days of the year which was caused by low flows in the rivers, faulty gates, leakages, sedimentation and breaches. Areas receiving less than 50% of the design discharge were unlikely to achieve any equity among the distributaries.

Due to design constraints, crops suffer during peak demands as the canals are always in deficit. This implies that it is impossible for the farmers to achieve maximum crop production.

1.4.2. Water availability constraints

As stated in Section 1.1, Pakistan is located in a water-short environment and the irrigation practiced here is based on the distribution of available water. Water balance studies carried out by Hussain et al. (2011) found that the total annual water available in the basin is 274 billion cubic metres (BCM). Gross water requirement in the agricultural sector is 210 BCM. Only 130 BCM (68 BCM consumptively used by crops while 62 BCM is lost through the system) is being supplied from surface water sources while 60 BCM is supplied from groundwater sources. The two sources are able to supply 190 BCM against the 210 BCM required indicating a deficit of 20 BCM. The study estimates that by 2015 the deficit in supply would be 27 BCM and will rise to about 34 BCM by the year 2025. With an expected rise in domestic and industrial water needs, the deficit in the basin will only increase beyond these estimates.

Precipitation varies in magnitude and time of occurrence in different parts of the country (Naz, 2010). Most of it is concentrated in the months of July-September (summer) because of Monsoons. The driest months of the year are April-June and October-November. Localised and sporadic convectional rain events accompanied by thunderstorms sometimes occur in these dry periods. The result is a constant fluctuation in river water levels. This in turn affects the amount of water that can be abstracted from the rivers via the main canals, majority of which are run-of-the-river (De Vries & Anwar, 2015). If the levels are too low or very high, the canals are closed. Canals are closed when the levels are too low to maintain the environmental flows in the rivers and when too high because the canals, being in-cut, have no storage which can accommodate any meaningful deviation from the carrying capacity and would result in flooding of the adjacent farms.

Naheed & Rasul (2010a) reported that rainfall amount and intensity in the basin has been decreasing with the temperatures rapidly increasing during summer months. This means that the proportion of water that flows in the rivers as a result of precipitation and runoff (up to 30%) is reducing thereby reducing the water available for diversion to the irrigation system.

1.4.3. Losses

Most of the conveyance system is not lined due to the size of the irrigation network. This means that there are conveyance losses in addition to evaporation losses. Studies conducted in the basin have put the conveyance losses between 25-55% (Condon et al., 2014; Qureshi & Fatima, 2012; Qureshi et al., 2008) and application losses between 25-40% (Qureshi & Fatima, 2012), leaving only 45% of the flow at the canal head remaining available to crops (Condon et al., 2014). It may not be economically feasible to line all the canals as they do not lose water uniformly and only patches that have been found to loose water excessively are lined. For example, Skogerboe et al. (1999) reported that Fordwah branch canal was losing 0.003 L/s/m while Hakra branch canal was losing 0.002 L/s/m. This could be corrected by lining, which was proposed to reduce seepage by a factor of between 50-90%. The cost of lining ranged between PRs 1,329 to 1,697 per metre of canal (2011 PRs) (Shah et al., 2011). If it is assumed that all the whole canal system was to be lined (1,660,000km), the capital outlay that was needed ranged between PRs 2.2-2.8 trillion or US$267 - 34 billion (1 US$=85.72 PRs on average in January 2011).

Estimated canal efficiencies are shown in Table 1-2 (Aslam & Anwar, 2014). Individually, each component shows some acceptable efficiency but when all are combined, the overall efficiency is very low.

Table 1-2 Canal irrigation efficiencies

System Component	Delivery at head (BCM)	Losses (BCM)	Efficiency (%)
Main and Branch Canals	130	19	89.4
Distributaries and minors	86	8	92.2
Watercourses	102	30	69.9
Field	71	20	70.7
Crop use	50		
Total losses		**77**	
Overall irrigation efficiency			**38.7**

BCM denotes Billion cubic meters

1.4.4. Over-irrigation, drainage and salinity

Condon et al. (2014) report that when irrigation scheme started, over-irrigation did not seem possible, but with extensive construction of water infrastructure and distribution of water in the basin, over-irrigation occurred. Over-irrigation led to a disturbed water balance which caused water logging and salinity. Seepage from unlined canals also contributed in the rapid raise of the water table in the basin. The irrigation scheme was designed without surface or subsurface drainage system as water provision, rather than drainage, was considered a priority. The natural water table pre-irrigation was between 20-30m below soil surface but by mid-20th century, it was within 1.5 m of the soil surface (A. S. Qureshi et al., 2008) as illustrated in Figure 1-4.

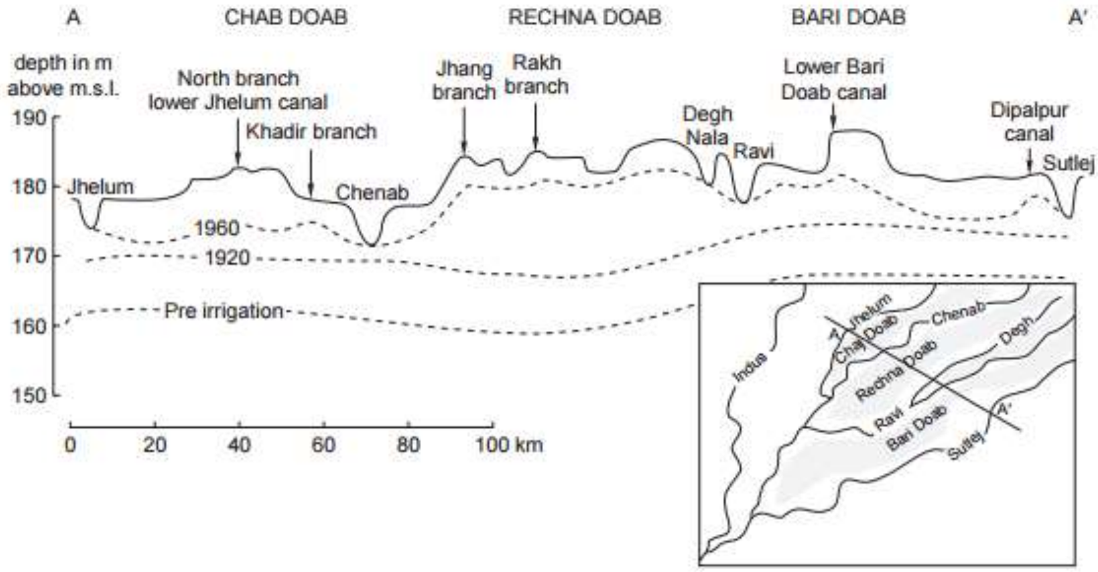


Figure 1-4 **Change in groundwater level in Punjab between1860 and 1960 (Wolters & Bhutta, 1997)**

This rapid rise in water table caused two major problems. First, it inhibited crop growth in the areas where the water reached the surface. Second, the natural salts in the alluvial deposits (Bhutta & Smedema, 2007) were moved into the root zone and higher up the soil column by water in solution form. When the water evaporated, dried salt crust and crystals remained on the land which affected its quality. 30% of the previously usable farmland was left either too soggy by the elevated water table or affected by salinity by the end of 1950s (Condon et al., 2014; Qureshi et al., 2008).

To address this situation, the Salinity Control and Reclamation Project (SCARP) was established in 1960s (Kijne & Kuper, 1995) under the Punjab Soil Reclamation Act of 1952. Under this project, 14,000 high capacity tubewells (80 L/s) were installed to pump non-saline groundwater into canals to supplement the surface flows while the saline water was pumped into the drains (Condon et al., 2014).

The additional water that was supplied by the SCARP tubewells led to increased cropping intensities from 80% to 120-150% in the SCARP areas (Qureshi et al., 2008). Farmers in other regions that were not covered by the SCARP project realised that installing private tubewells in their plots was beneficial to their crops. It is estimated that about one million private tubewells have been dug to serve over 2.5 million farmers both in isolation and in conjunction with surface water to contribute up to 50% of irrigation water (Condon et al., 2014). The vertical drainage project worked well initially until the tubewells started breaking down due to high operation and maintenance (O&M) costs, with some being completely shut down. This resulted in a shift from vertical drainage to horizontal drainage especially in the Sindh province.

The surface water used for irrigation in Pakistan is of excellent quality with salinity levels of 150-250 mg/L (0.2- 0.5 dS/m), sodium absorption ratio (SAR) of 0.2 (meq/L)$^{0.5}$ and residual sodium carbonates (RSC_{iw}) of -0.4meq/L (Condom et al., 1999). Soil salinity is intrinsic in the Indus basin due to soil forming processes (Aslam et al., 1999; Qureshi et al., 2008). Continuous irrigation has resulted in an annual salt inflow of 33Mg from Indus River and its tributaries in to the basin. Only 9 Mg is flushed out of the system and 24Mg retained in the basin of which 13.6Mg is stored in Punjab province.

Supplementation of surface water with groundwater for irrigation further aggravates the problem of soil and water salinization. It is estimated that 28.2Mg of salt is deposited annually on the soil surface from water drawn from tubewells. Salts deposited from tubewell water are fossil salts from deeper aquifers and strata. (Qureshi et al., 2008).

1.4.5. Sodicity

Apart from causing salinity due to saline water circulation, groundwater is also causing sodicity. Studies done by Qureshi et al. (2008), indicates that 70% of tubewells in the basin are producing sodic water (high concentration of sodium (Na^+), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-)). Work done by Kijne & Kuper (1995) in the Upper Gugera, Lower Gugera and Fordwah/ Eastern Sadiqia commands indicated that the areas had SAR ranging from 3.1-17.5. SAR values less 13 are considered to be non-sodic, 13-25 are slightly sodic, 25-45 are moderately sodic and any value greater than 45 is strongly sodic (Qureshi & Barrett-Lennard, 1998). It was estimated that the SAR values would go up with the continued use of groundwater for irrigation. Sodic soils can cause swelling, slacking, dispersion of clay, surface cracking or hard setting which can affect air and water circulation/movement, plant available water holding capacity, root penetration, runoff, erosion, seedling emergence and sowing and tillage operations. Widespread use of gypsum is carried out in areas suspected to be experiencing sodicity (Qureshi & Barrett-Lennard, 1998).

1.4.6. Sedimentation

The system is suffering from sedimentation. Monsoon rainfall is responsible for the excessive erosion of the hilly catchment areas with the runoff depositing the sediments in the river (Aslam & Anwar, 2014). Suspended sediments are usually diverted in to the conveyance system where they fall to the bottom of the canals due to decreased velocities while further sediment settles out in the reservoirs. Sediments deposited in the reservoirs reduce the storage capacity while those deposited in the canals reduce the carrying capacity leading to inadequate water supply to the off-taking and watercourses.

Punjab province lies in an area characterised by flat topography. There is no adequate slope to allow water to carry the silt load to the tail end of water distributaries and minors and hence none is flushed from the system. There are currently no simple methods of disposing silt laden water from the canals system (Ul Haq, 1998).

1.4.7. Financial issues

There is need to carry out other operation and maintenance (O&M) practices in the irrigation system. O&M requires a substantial amount of money to be carried out effectively but there is little available (Sufi, 2011; Ul Haq, 1998). A study carried by Ul Haq (1998) attributes the following to be the cause of financial issues:

- Inadequate maintenance funding leading to differed maintenance of the irrigation infrastructure. The budgeting that was done in 1992 is still used today without taking into consideration increased cost of labour or materials and inflation.
- Sub - optimal use of O&M funding as a result of biasness in funds distribution, delayed release of funds, wrong priorities and lack of financial discipline.
- Stagnation of collection of abiana (water charges).
- Abiana is not adjusted to conform to inflation.
- Increased maintenance expenditure of public tubewells.

For example, Sufi (2011) found that the total cost of O&M for the irrigation system was PRs. 9.41 billion against a collection of PRs 2.65 billion which could only cover 28% of the works needed.

1.4.8. Other issues

Other operational issues that have been identified in the region include (Ul Haq, 1998);

- Lack of measurement structures;
- Inadequate standards;

- Outdated maps, files and inventory of facilities;
- Minimal farmers participation in evolving operational plans and their implementation;
- Lack of interagency co-ordination;
- Running canals beyond their designed capacities in order to meet increasing water demand which affects the canals' regime and their operational safety and distribution patterns due to raised water levels;
- Increased incidences of outlet tampering and other regulation structures in combination with breaches of the canals which causes alterations in the established operational patterns;
- Lack of adequate canal supervision as the field workers have to supervise long reaches of canals. All field workers work in one eight hour shift while the canals run for 24 hours;
- Due to the fact that most canals are in-cut and that they carry excess flows; there are long berm-less reaches. These reaches are always threatened by the presence of burrowing animals as they may create weakness leading to flooding in the adjacent fields;
- Flooding problems especially after intense monsoon rainstorms in the upper river catchments. Inadequate flood forecasting systems, highly active and meandering river channels, inadequate cross drainage capacities on hill torrents and financial constraints hinder effective flood protection and maintenance of river training works;
- Technological stagnation in the form of an unreliable forecasting system for expected river flows, absence of database for the irrigation system, inability to acquire real time data etc.

1.5. Service interruption

The Punjab Irrigation Department (PID) enables the farmers to irrigate their crops by providing water in the distributaries so that they can divert their share into their farms. If the PID is not able to deliver water to the distributaries, there is service interruption. Service interruption can be defined as a no water period among the farmers (canal closures) (De Vries, 2014) as opposed to irrigation scheduling which is division of water among farmers (Martin, 2001). De Vries (2014) and De Vries & Anwar (2015) break down service interruption in to two components: quantity delivered and the frequency of delivery. Data collected during Kharif 2014 indicate that not only is the evapotranspiration higher than the design discharges as shown in Figure 1-5, but also actual water delivered is lower than design discharge as shown in Figure 1-6.

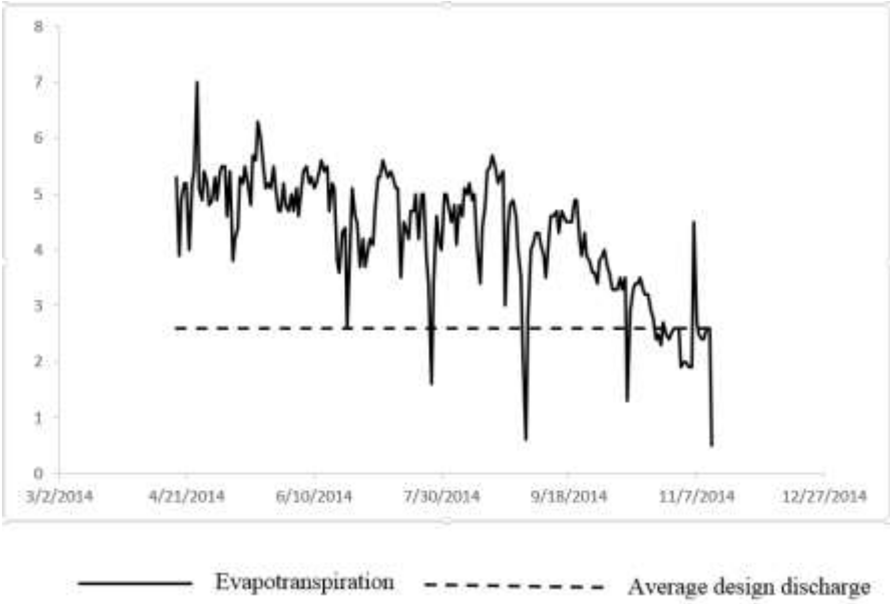


Figure 1-5 Evapotranspiration and deign discharge for HBC, Kharif 2014 (De Vries, 2014)

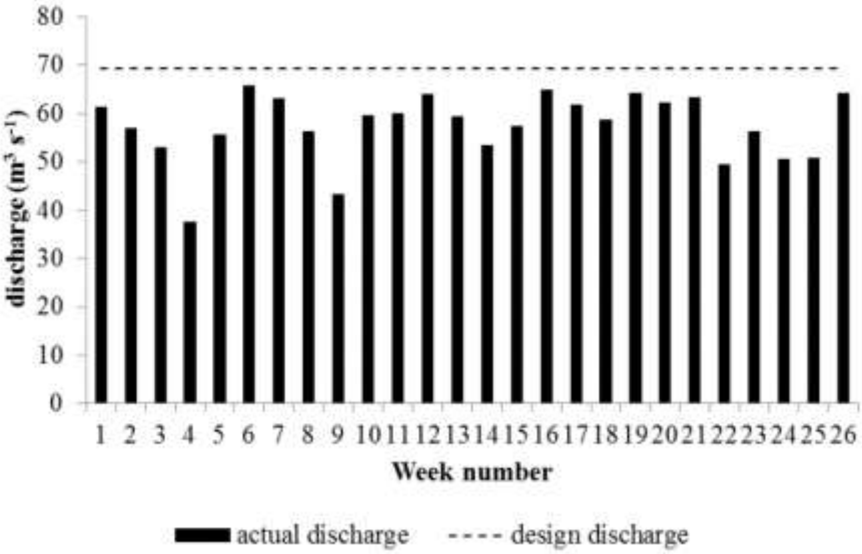


Figure 1-6 Actual and design discharges for HBC, Kharif 2014 (De Vries & Anwar, 2015)

As the service provider, the PID has to decide on how to distribute water in terms of quantity per distributary and the distributaries that need to be closed or opened. There are schedules that are followed in water allocation which were designed based on the experience of the water/irrigation engineers in the field. Different canals are grouped together and priority as to which group is to receive water differs from one week to another. Studies done on HBC by De Vries (2014) on the existing schedules indicate that the 17 distributaries on HBC received an average of 93% of their target allocation in Kharif 2014. One of the distributaries received about 148% of its target while another one got only 56%. This shows that the schedules run by the PID create inequities in service provision and uneven water supply. This makes it difficult for the farmer to fully appreciate the service and may result in non-payment of water levy. It also means that the schedules go against one of the principles of Warabandi: equity. Farmers who have access to groundwater use it to correct the uneven distribution and supplement surface water supply to improve on the production of their farms. The schedules should be designed to ensure that the distributaries receive equal amount of water, similar share of non-delivery of water and no distributary should be closed week after week as the chronic water shortage in Punjab cannot allow uninterrupted water supply to the farmers (De Vries, 2014).

When the duration of service interruption is too long, it is expected that the crop will suffer from water stress which in turn affects the yield. Various reasons, for example, infrastructure failure, inadequate water and scheduling have been known to cause service interruption as long as the mild water stress projected on the crops does not affect yields too much (Kirda, 2002). Since water is inadequate and has to be scheduled, De Vries (2014) set out a procedure to determine how the water delivered by PID would be scheduled in order to minimize water stress on crops.

1.6. Modelling

1.6.1. Introduction

A model is a representation of an actual system that makes it possible and easy to investigate properties of the system it represents by mimicking the processes of the system (Savary & Willocquet, 2014). A model can also be conceptual, mathematical or physical. Modelling is the application of a model to describe the performance of a system (Oteng-Darko et al., 2013) (simplified representation of reality (Savary & Willocquet, 2014)). A system is a set of interdependent objects which act to accomplish some purpose and are separated from each other by either physical or conceptual boundaries (Hillel, 1977). A model is used to help solve problems, both in academic and practical fields. The following five stages are applied when solving a problem using a model (Hillel, 1977):

a. Problem definition; there has to be a specific problem which needs to be investigated upon.
b. Model selection; this is done after identifying the key controlling factors of the problem. There exist a large number of models which have been applied to similar problems or can be modified to suit the current problem.
c. Model calibration; involves systematic adjustment of parameters to conform to known external benchmarks by applying parameters found in literature or subsidiary experiments.

d. Model validation; involves running a model to predict an already known outcome from previous data. This step gives the modeller confidence in the application of the model to predict future events.

e. Model application; here, the model is applied to the specific problem defined in step one. Adequacy of the model depends on the outcome and nature of the problem.

1.6.2. Model for service interruption scheduling

De Vries (2014) developed a linear programming model known as Equitable Canal Water Allocation (ECWA) model for scheduling canal closures so that service interruption is minimised. The model aims to reduce the length of service interruption by employing a penalty cost function. The model uses decision variable, objective function, hard constraints and soft constraints to model scenarios as explained by De Vries (2014). The model was developed using data provided by the PID for three growing seasons; Rabi 2010/11, Kharif 2011 and Kharif 2012. Daily Water allocation data was provided, along with weekly data on the decision to open or close a canal. The daily data was aggregated to provide weekly data and using a combination of different objective functions and equity costs, 10 scenarios of service interruption were modelled for all the distributaries. All the scheduling scenarios were modelled with an assumed lower threshold of 80% of the allocation target below which water stress would cause significant yield loss and anything greater than 120% would pose a risk of waterlogging and salinity issues with similar result in yield loss. The weeks when HBC was completely closed for cleaning and maintenance were omitted as this would create a scenario where a distributary would go without water for five weeks.

The suitability of each scenario of scheduling was determined using the Gini index (measure of inequity) as described by Anwar & Haq (2013). The Gini index calculations concluded Scenario A created the most inequitable schedules while Scenario I created the least (De Vries, 2014). Comparison between current schedules (PID schedules) and the ECWA model schedules revealed that the current schedule fared better than Scenario A schedules for Kharif 2014 but they performed worse than both Rabi 2014/2015 and Kharif 2015. The Gini index for PID, Scenario A and I is shown in Figure 1-7.

The ECWA model did not consider the effects of the new schedules on crop yield, salt accumulation in the root zone and root zone depletion at the end of the growing season. De Vries (2014) suggested that the effects of these schedules needed to be determined either by field trials or by using a crop water productivity model.

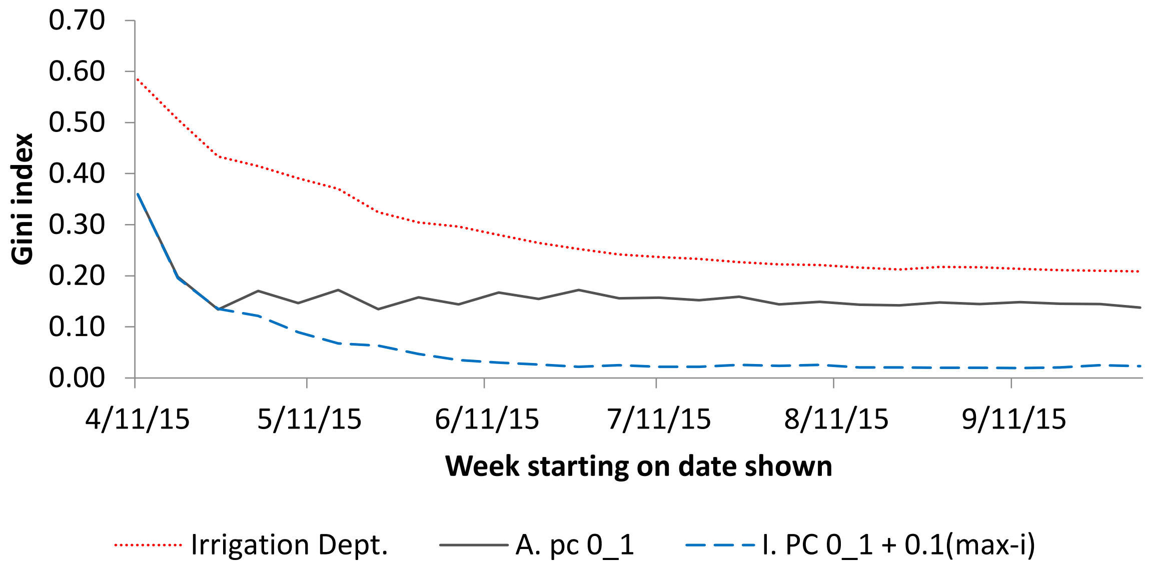


Figure 1-7 **Gini Index for PID, Scenario A and I, Kharif 2015 (present study)**

1.6.3. Crop growth models

A crop growth model is a tool that predicts the growth of plant based on environmental conditions, managerial decisions and variables describing the plant's parameters (Gommes, 2001). The performance of the plant is mostly gauged on the amount of biomass stored in different organs. To mimic the behaviour of a real crop, the model is executed as shown in Figure 1-8 .

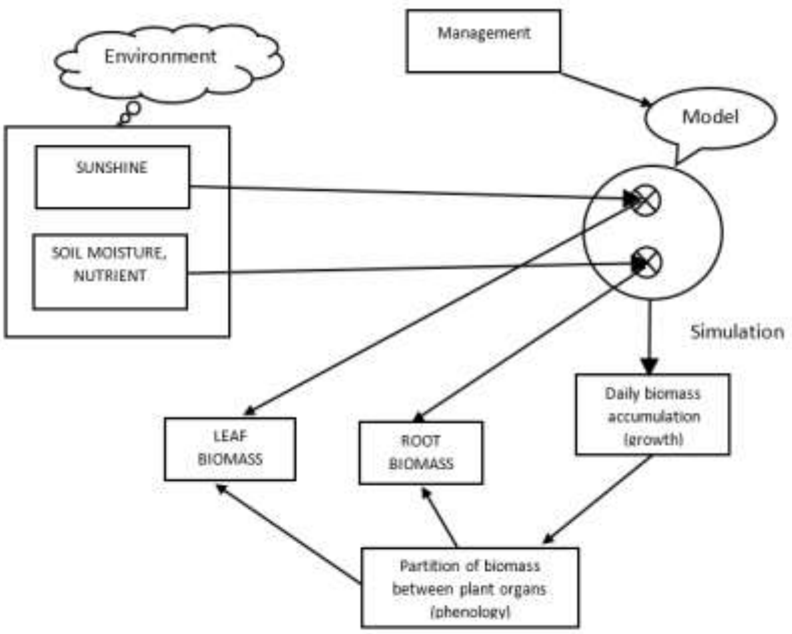


Figure 1-8 **Schematic representation of a crop growth model (Gommes, 2001)**

Models are designed to incorporate three key steps; model processes, model inputs and key model outputs (Table 1-3).

Table 1-3 Key steps in a model

Model Processes	Model Inputs	Model Outputs
Phenological development	Meteorological variables	Yield forecasting
Light interception and utilization	Soil properties	Environmental characterisation
Root distribution	Cultivar parameters	Optimal crop management practice
Soil water dynamics	Management	Impact of climate change
Soil nutrient dynamics		Optimal sowing dates for hybrid seed production
Evapotranspiration		Research understanding
Environmental stress		Yield analysis
Effects of elevated carbon dioxide (CO_2)		

Source (Carter, 2013; A. K. Singh, 1994)

Model processes and inputs vary across different models as the model processes are based on the driving parameters behind a particular model. For example, models can have limiting factors such as water, thermal time, land management practices or solar radiation (plant carbon accumulation) (Hunink et al., 2011). The main limiting factor will in turn determine the number of parameters that are needed to run it.

1.6.4. Types of crop growth models

Crop growth model are classified according to the purpose for which they are designed for. The two broad categories that of model classification are (Hillel, 1977):

a. Empirical models – models that directly describe observed data. They are expressed in regression equations using one or a few factors give an estimate of final yield. The models are usually opaque in that they do not provide information on the steps used to provoke the response. Examples of these models include those used to show response of crop yield to fertilizer application or relationship between leaf area, leaf size and stalk height or diameter to final yield.

b. Mechanistic models – models that define the processes of a system in terms of lower- level characteristics, for example, cell division. They have the capability of simulating the relevant physical, biological or chemical processes and to describe how and why the system produces a particular response. The modeller can explain the results, say final yield, by combining previous experience in the subject and knowledge gained through introduction of additional parameters and variables.

These two broad categories can further be classified as (Oteng-Darko et al., 2013)

i. Static and dynamic models – static models do not incorporate time as a variable even if the end products of cropping systems (yields) are accumulated over time while dynamic models explicitly incorporate time as a variable.

ii. Deterministic models – these are models that make definite estimates for quantities, for example, crop yield or rainfall, without any associated probabilities, variance or random elements. Inaccuracy in recorded data and heterogeneity in material being studied which are integral to biological and agricultural systems cause variations in outputs.

iii. Stochastic models – are models which give expected mean and associated variance in a system with high level of variation and uncertainty. They tend to be technically difficult to handle and become complex fast. These models should only be used when results from deterministic approach are inadequate and unsatisfactory.

iv. Simulation models – are models designed to mimic the processes of a system in short time intervals (daily time step). They capture variability related to daily change in weather and soil conditions. They require large amount of input data-climate parameters, soil parameters and crop parameters due to the short simulation time step. The models offer modules where the user can specify management options.

v. Optimizing models – are used to evaluate the best options in terms of management inputs for practical operations of the system. They employ decision rules that are consistent with optimizing processes.

Examples of crop growth models that have been applied for this kind of studies include:

- Agricultural Production Systems Simulator (APSIM);
- AquaCrop;
- CropWat;
- Crop Systems Model (CROPSYST);
- Decision Support System for Agrotechnology Transfer (DSSAT);
- Simulateur Multidisciplinaire pour les Cultures Standard (STICS);
- Soil-Water-Atmosphere-Plant (SWAP);
- Soil and Water Assessment Tool (SWAT);

- WaSiM (Water Flow Balance Simulation Model);

These models have different model drivers and data requirements as shown in Table 1-4.

Table 1-4 Model drivers and data requirements.

Model	Model Driver	Data set required
APSIM (Keating et al., 2003)	Soil characteristics specifically moisture and hydraulic conductivity of each soil layer; Nitrate nitrogen; Residues;	Daily weather data, Soil characteristics Crop data; Crop management actions; Simulation period.
AquaCrop (FAO, 2013a)	Water	Daily weather data; Crop data; Management actions; Soil characteristics; Simulation data.
CropWat (FAO, 2013b)	Water	Daily weather data; Crop data; Management actions; Soil characteristics; Simulation data.
CROPSYST (Stöckle et al., 2003)	Water, nitrogen	Location (climate); Soil data; Crop data; Management actions.
DSSAT(Jones et al., 2003)	Multiple drivers depending on the mechanistic models used	Climate data; Management data; Soils data; Mechanistic crop model (CERES, CROPGRO etc.); Soil-Plant-Atmosphere; Crop data.
STICS (Brisson et al., 2003)	Daily climatic data	Climate data; Soil characteristics; Management actions; Genetic parameters.
SWAP (Hunink et al., 2011; Ines et al., 2001; van Dam et al., 2008)	Soil hydraulic properties (Solution to Richard's equation requires definition of initial, upper and lower boundary conditions)	Weather data; Soil data; Crop data; Initial, upper and lower boundary conditions; Management actions.

Model	Model Driver	Data set required
SWAT (Hunink et al., 2011)	Land management practices	Climate data; Soil characteristics; Land characteristics (topography and vegetation); Land management practices.
WaSiM (Cullmann et al., 2006)	Hydrology event (rainfall); Land use;	Climate data; Soil data; Raster data for topography; Crop data; Irrigation data Drainage data.

1.6.5. Crop model limitations

Each model has been designed to perform specific tasks. The models are important analytical tools that provide understanding and clarity on how different components of the system interact and work but must be used carefully. Proper application of models comes from understanding their shortcomings and ensuring that such shortcomings are addressed when performing simulations and analysis. Some of the limitations include (Oteng-Darko et al., 2013; Richardson et al., 1979):

a. Models are incomplete – accurate projections are impossible because real world systems are complex and composed of many interrelated components which are simplified in the model. Biological and agricultural models represent systems for which the processes and interrelations of components are not fully understood. The model designer tries to simplify these interrelations between components due to the limited knowledge. This will of course interfere with the accuracy of the projection.

b. Models assume the future and the past are consistent – models are designed to represent a system /process based on historical data and yet they are used to predict what will happen in the future. The future is always changing and hence this assumption is not necessarily valid.

c. User capability – not all users are expert in the field of modelling and hence misuse of the model might occur.

d. Quality of data – good quality data is a key for better results. Most models use meteorological data as the raw data and hence it should be complete and reliable. In other cases above ground data of cropping systems is so large but that relating to the root growth and expansion and soil characteristics is not much. This creates a data gap which in turn affects the quality of output generated by the model. There are cases of errors in sampling data which also contribute to inaccuracies.

e. Difficulty in model validation - this is because field data are not definite. Some parameters and driving variables might not be measurable at the present site and are often borrowed from nearby sites and hence not precise. Also, measurement of some parameters is routinely ignored. These parameters might be important for the model and so they are arbitrarily estimated. Effects of soil heterogeneity over small distances as well as effects of husbandry practices on the soil often cause variation in measured data. These variations are sometimes assumed to ease validation thus affecting results.

1.7. Major Crops

The major crops grown in Punjab province are cotton, wheat, rice and sugarcane (Kahlown et al.,1998) but for this research only cotton and wheat were studied.

1.7.1. Cotton

Cotton (*Gossypium spp*) is woody, perennial, C_3 photosynthetic crop, grown for its fibre and its seeds due to their high oil and protein content (Steduto et al., 2012). The most common variety of cotton grown is Upland cotton (*Gossypium hirsutum*). Cotton thrives in well between tropics and latitudes as high as 42˚ but requires sufficient sunshine, warm temperature, long frost-free periods and moderate rainfall (600-1200mm) which can be substituted with irrigation when required. Rain fed cultivation achieves substantial yields but often, irrigation is required to achieve optimal and consistent yields (Steduto et al., 2012). It has indeterminate growing cycle: the crop usually takes anywhere between 130-195 days depending on the region where it is planted (FAO, 2015). Some of the distinct stages in cotton development are germination, emergence, squaring (formation of flower buds), early flowering, peak flowering, boll formation and boll opening (Meerbach, 1997).

As stated in Section 1.1, Pakistan lies between latitudes 22.5 and 35˚ N. This means that the country lies in appropriate latitudes for cotton production. Cotton is cultivated in Punjab and Sindh provinces because they meet most of the cotton growth criteria, with the exception of annual rainfall which is about 240mm/year. This means that cotton production cannot achieve substantial yield without irrigation. Pakistan is a major player in the world of cotton production. It is the fourth largest cotton producer for total yield in the world but it is ranked seventh for yield per hectare as shown in Table 1-5. Lower yield per hectare as compared to other countries could be attributed to type of irrigation method used, type of seed used, low soil fertility, soil salinity and water logging, inadequate fertiliser use, pests, diseases, inadequate irrigation water and excessive high temperatures during flowering (Ali et al., 2009).

Table 1-5 Top cotton producing countries

Country	Production in million tons – 2014 estimates*	Yield* (kg/ha) – 2014 estimates
China	6,967	1,484
India	6,641	514
United States	2,811	903
Pakistan	2,068	757
Brazil	1,633	1,563
Uzbekistan	904	661
Australia	893	2,281
Turkey	501	1,620
Turkmenistan	327	579
Greece	298	1,007

*Yield is reported in terms of lint produced

Source: IndexMundi (2015a) and The Statistical Portal (2015b)

There are several varieties of cotton gown in Punjab and Sindh provinces but the main distinction is between Upland cotton (*Gossypium Hirsutum)* and Desi cotton (*Gossypium Arboreum).* Desi cotton is characterized by short lint, lower water and fertilizer requirements, higher resistance to viruses (hence higher yield security) and a longer growing season, usually one month longer than Upland cotton. Desi cotton is not as popular as Upland cotton. Crop acreage statistics carried out Bureau of Statistics (2012) shows that out of 2,201,000 ha under cotton, only 45,000ha (2%) were under cotton in Kharif 2010-2011.

Good germination of cotton seedlings is essential as the quantity and quality of lint harvested depend on it. A well prepared seedbed with enough soil moisture, oxygen, conducive soil temperature (higher than 17˚C) and low salinity in the topsoil together with good quality seeds will guarantee a good germination. Low salinity in the topsoil is necessary as the germination stage is most sensitive to saline conditions. Conducive soil temperatures are usually achieved in Kharif. This means that cotton is planted after wheat is harvested. Farmers in cotton growing season have established a sequence of activities in order to create a good seedbed (Latif et al., 2008; Meerbach, 1997). The activities are:

a) Wheat harvest usually at the end of April;
b) Ploughing to remove wheat stubbles and condition the soil
c) Rauni (pre irrigation)-usually done to bring the maximum root zone up to or close to field capacity;
d) Levelling –to achieve irrigation uniformity;
e) Sowing –either by use of a tractor and a drill or oxen and plough on either bed furrows or flat and alternate furrows.

The recommended seed rate deepens on the type of seed available and the sowing method. One hectare will take between 8-10 kg of fuzzy seeds while the same area will require 4-6 kg of delinted seed. Flat sowing with alternate ridging accommodates about 61750-74100 plants/ ha while bed furrow sowing usually take up 144,928 plants/ha (Ali et al., 2010)

The recommended planting date for cotton is mid-May but most of the farmers plant between second week of June and beginning of July. This delay has been attributed to labour constraints, insufficient canal water, bad germination, lack of tractors and occurrence of early rains (Ali et al., 2009).The delay encourages reproductive growth as opposed to vegetative growth because the crop is slightly water stressed. Adequate water is needed for the plant to achieve vegetative growth necessary for flower formation.

Water use and water productivity (WP) depend on irrigation method and the amount applied. Water productivity is crop yield per cubic metre of water used and it depends on crop patterns, climate patterns, irrigation technology and field management (Cai & Rosegrant, 2003). Steduto et al. (2012) state that the WP[1] $_{lint/ET}$ improves from 0.33kg/m^3 to 0.15 kg/m^3 when furrow irrigation is substituted for drip irrigation. Lower WP $_{lint/ET}$ for drip irrigation is attributed to reduced soil evaporation. Furrow irrigation is mainly used to grow cotton in Pakistan. Studies carried out by Singh et al. (2006b) in Sirsa district India (similar climatic conditions and irrigation method to Punjab Pakistan) shows average WP[2] $_{Y/ET}$ of 0.23 kg/m^3.

Harvesting of mature bolls usually start around early October and is mostly done by hand especially by small scale farmers and where Desi cotton is planted. On average, most farmers take about 52 days to harvest all the available cotton. This means that cotton stays in the field up to end of November and beginning of December (Arain, 2012; Meerbach, 1997).

[1] WP $_{lint/ET}$ – WP as the ratio of lint of cotton to evapotranspiration (kg/m^3)
[2] WP $_{Y/ET}$ – WP as a ratio of yield as dry matter to evapotranspiration (kg/m^3)

1.7.2. Wheat

Wheat (*Triticum aestivum*) is a C_3 plant that is grown in the arctic and humid regions as well as the tropical highlands and from altitude zero (sea level – Dutch Polders) to altitude 4,500m (Tibet) (Steduto et al., 2012) although it is most productive between latitudes of 30˚ and 60˚ N and 27˚ and 40˚ S (Curtis et al., 2002). Due to the ability of the crop to grow in diverse climatic conditions, it is the third largest crop in the world with 710 million metric tons produced in 2013/2014 (The Statistical Portal, 2015a). As of 2014 estimates, Pakistan was ranked as the seventh largest wheat producer in the world with 24 million metric tons with a yield of about 3 tons/ha as shown in Table 1-6. Wheat is regarded as number one staple food in the country.

Table 1-6 Top wheat producing countries

Country	Production (thousand metric tons)	Yield (metric tonne/ha) – 2014 estimates
China	121,720	5
India	93,510	3
United States	57,961	3
Russia	52,091	2
Canada	37,500	3
Australia	27,000	2
Pakistan	24,000	3
Ukraine	22,278	4
Turkey	18,000	2

Source: The Statistical Portal (2015a) and IndexMundi (2015b)

Wheat is usually grown in rotation with a variety of other winter annual crops such as cereals, oilseed crops and pulses. In Punjab, it is mainly grown in Rabi in rotation with either rice, cotton and maize or sugarcane (Byerlee et al., 1986; Kahlown et al., 1998) but the most common rotation systems are rice-wheat and cotton wheat. To minimize risk of high temperatures during the flowering and grain filling stages, the planting date is timed to fall anywhere in the last three weeks of November but this is not always the case. Delayed sowing has been attributed to late harvesting of the previous crop (cotton and basmati rice) and long turnaround between the rice/cotton harvest and wheat planting (caused by excessive tillage, unfavourable soil conditions and poor power sources) (Hobbs et al., 1998). Figure 1-9 shows factors that influence planting date of wheat in cotton-wheat rotation.

Normal sowing depth for wheat is around 5cm but greater depths may be used especially in dry conditions in an attempt to place the seeds into moist soils. Any of the following methods is used in Punjab to sow the cereal (Soomro et al., 2009):

- Broadcasting - seeds are scattered in the field and harrowed in to cover them;

- Behind local plough - seeds are dropped by hand into farrows that have been opened using plough drawn by animals;
- Drilling - a seed drill is used to place seeds at a uniform depth resulting in uniform germination and regular stand;
- Dibbling - a dibbler is used to drop one or two seeds in the soil especially when supply of seeds is limited;
- Zero tillage technique - direct sowing is done using a drill without prior land preparation.

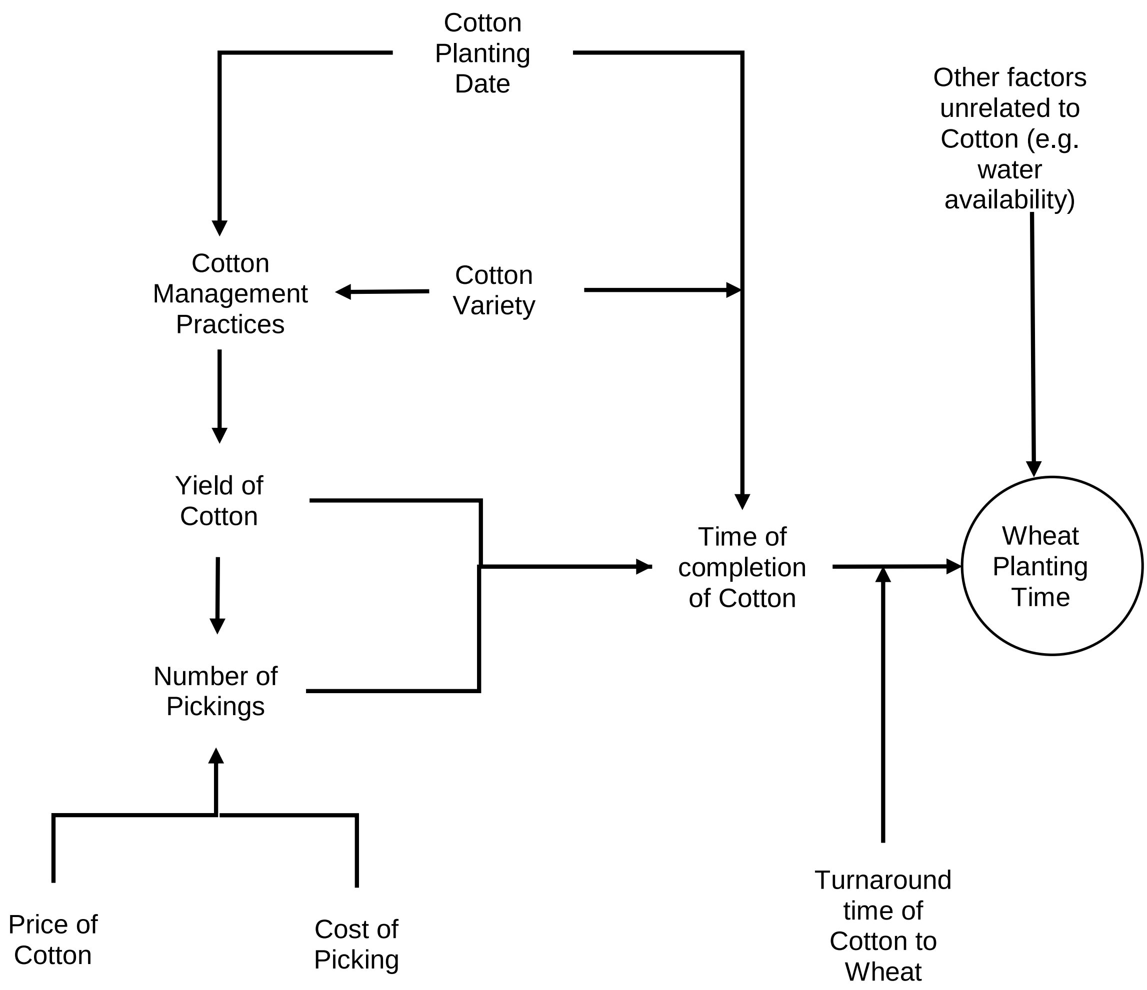


Figure 1-9 Factors affecting wheat planting in cotton-wheat rotation (Byerlee et al., 1986)

Depending on the method of sowing selected, the plan densities in the farms usually vary from 50-500 plants/m^2 (lower densities are used in drier conditions) (Steduto et al., 2012). Most of the farmers in Pakistan use a seed rate of 90-95 kg/ha (135-142 plants/m^2) (Aslam, 1998).

Development of wheat is temperature dependent (Porter & Gawith, 1999). The crop requires a minimum mean daily temperature of 5˚C but for optimum growth, the mean daily temperature should be between 15˚C and 23˚C. Data collected at the Haroonabad weather station indicates that the mean daily temperature vary between 5˚C (December) and 28˚C (March) during Rabi. Due to delayed planting and using of winter resistant cultivars (some of which have been known to survive down to -20˚C during early development stages), head development and flowering are not affected by the low temperatures (Porter & Gawith, 1999; Steduto et al., 2012). The crop does not encounter frosty period during flowering and head development which could result in loss of spikelets and in extreme cases the whole head, as the crop's resistance to cold is lost during active growth period.

Wheat is affected by inadequate water when tillers are developing and their abortion rate is highest, during bud (florets) formation, grain setting and during grain filling (Steduto et al., 2012) hence irrigation is required if these activities coincide with periods of inadequate rainfall. Too much water especially in vegetative period, resulting in water logging, can lead to reduced yield as low oxygen levels can lead to root damages and hence water and nutrients uptake. Water use productivity (WP) for the crop in Punjab, as well as other places, depends on irrigation method used and ranges from 5.21kg/m^3 for sprinkler irrigation to 1.38 kg/m^3 for basin irrigation (Kahlown et al., 2007)

The crop takes between 85-145 days to reach maturity depending on the prevailing climatic conditions (Steduto et al., 2012). In Punjab province, the crop is harvested between 114-142 days after planting (Kalwij, 1997). The method of harvesting, either by hand or using a combine harvester, depends on size of the farm and capital available to hire the machinery.

1.8. Summary leading to this research

As seen in Section 1.4, there are a number of problems that affect the irrigation systems of Pakistan. To solve most of these problems, money is required. For example, between US$ 26.6-34 billion would be required to minimise losses occurring due to unlined canals. But such an undertaking might not be practical because the financial and economic analysis would probably yield an internal rate of return that would make the whole project unviable. There is no way to change the design of the system without land reforms which might not be popular with the owners. The water availability will continue being strained by the population pressure and climate variability in the region.

Using the available resources, it is possible to ensure more equitable water distribution, the core principle of Warabandi system, among the farming community. This can be achieved by tasking the irrigation authorities to develop better irrigation scheduling and service interruption which would be more appealing to farmers. A service interruption scheduling model, ECWA model, has been developed by De Vries (2014) which allows equitable distribution of no water periods among farmers.

The model employs the Gini index to determine the most equitable scenarios of scheduling. However, these scenarios have not been tested to determine their effect on the various parameters that affect crops and soil.

By employing an appropriate crop water productivity model, the suitability of these scheduling scenarios can be investigated without disrupting the status quo of the farmers in the field. The models are cheaper as compared to practical implementation and will also accomplish the simulation of the effects faster. When these effects are known, the best scheduling scenario can be adopted or the better one can be customised to suit the situation on the ground.

This research is geared towards using a crop water productivity model to investigate the effect of using the service interruption scenarios in the Hakra Branch Canal (HBC) command area of Punjab Province in Pakistan. The parameters of interest include the yield, conjunctive water use, salt accumulation in the root zone and root zone depletion at the end of growing season. Conjunctive water use refers to either the simultaneous use of water from various sources such that water is mixed before application to the crops or separate use of water from various sources, that is, depending on a single water source for each application (Murray-Rust, 2002).

CHAPTER 2: RESEARCH AIM, OBJECTIVES AND METHODOLOGY

2.1. Description of the problem.

Farmers in Pakistan plant their crops under a range of planting dates as dictated by the prevailing weather conditions, water availability, and market availability or as advised by the agricultural extension staff (Directorate of Agriculture, 2015). These diverse planting dates may have an effect on the achievable yield, amount of conjunctive water used, root zone depletion and the accumulation of salts in the root zone due to the different climatic conditions that the crop is exposed to at different growth stages. In Punjab, the primary source water source is canal water while the secondary water sources are groundwater and rainfall.

Apart from planting dates, service interruption is thought to have an effect on achievable yield, amount of conjunctive water used, root zone depletion and the accumulation of salts in the root zone. PID is responsible for drawing up and implementing the service interruption schedules in Punjab region. These schedules have been developed from field/irrigation engineers' experiences rather than any particular scientific approaches (De Vries & Anwar, 2015) but due to the design of the system, inequitable distribution of water among the farmers exists. This inequity goes against the principles of Warabandi system. The inequity in the system drives farmers to look for alternative water sources, usually groundwater from tubewells. Extra costs are associated with tubewell water use due to pumping costs. Those who do not have tubewells on their farms have to buy water from their neighbours. Electric conductivity of tubewell water varies between 0.3 to 4.6 dS/m with the average for most wells being 2.5dS/m (Qureshi et al., 2003). Continued supplementation of surface flows with tubewell water has led to a net deposition of about 28Mg of salts annually in Punjab region thereby affecting the quality of soil in many places (Qureshi et al., 2008).

To improve equity in the system, new schedules have been developed using ECWA model (De Vries, 2014). These new schedules have been shown to address the issue of inequity but need to be tested to establish if their effect on achievable yield, amount of conjunctive water used, root zone depletion and the accumulation of salts in the root zone is better or worse than the PID schedules. Testing can either be in practice or by using a crop growth model. Using a crop growth model has been selected as it is cheaper and easier to simulate these effects before the schedules are implemented in the field.

2.2. Research aim and objectives.

The aim of this research is to quantify the effect of the ECWA model scheduling on crops and soils under the Warabandi water management system in HBC command area of the Punjab province, Pakistan. The main objectives of the research are:

a. To determine the effects of different planting dates and scheduling scenarios on achievable yield;
b. To determine the effects of different planting dates and scheduling scenarios on conjunctive water use;
c. To determine the effects of different planting dates and scheduling scenarios on root zone depletion;
d. To determine the effects of different planting dates and scheduling scenarios on salt accumulation in the soil profile.

2.3. Study Area: Hakra Branch Canal (HBC)

The study area is located in the Punjab province, Pakistan. Figure 2-1 shows the Hakra Branch Canal (HBC) which is located in the Fordwah Eastern Sadiqia command area and serves an area of about 200,000 ha. It is a run-of-the-river system like most canals in Pakistan and originates from Fordwah Eastern Sadiqia Main Canal which takes off from Sutlej River at the Sulemanki headworks and then trifurcates into Malik Branch Canal, HBC and Sirajwah Distributary (Waheed-uz-Zaman & Hamid, 1998). HBC divides further into 17 distributaries, numbered sequentially on each side of the canal (1R to 9R on the right, 1L to 4L on the left and the last four have proper names – Bakhu Shah, Flood Channel, Hakra Left and Hakra Right) (Anwar & Haq, 2013; De Vries, 2014; De Vries & Anwar, 2015).

HBC, as with other canals in province, is operated on a roster due to inadequate water supply in the system (Anwar & Haq, 2013). HBC command has been selected for this study as it has a distributary, Hakra 5R, which is well instrumented and has good quality data available. International Water Management Institute (IWMI) Haroonabad Office weather station is about 8 km from Hakra 5R Distributary offtake and is well equipped and managed by IWMI–Pak.

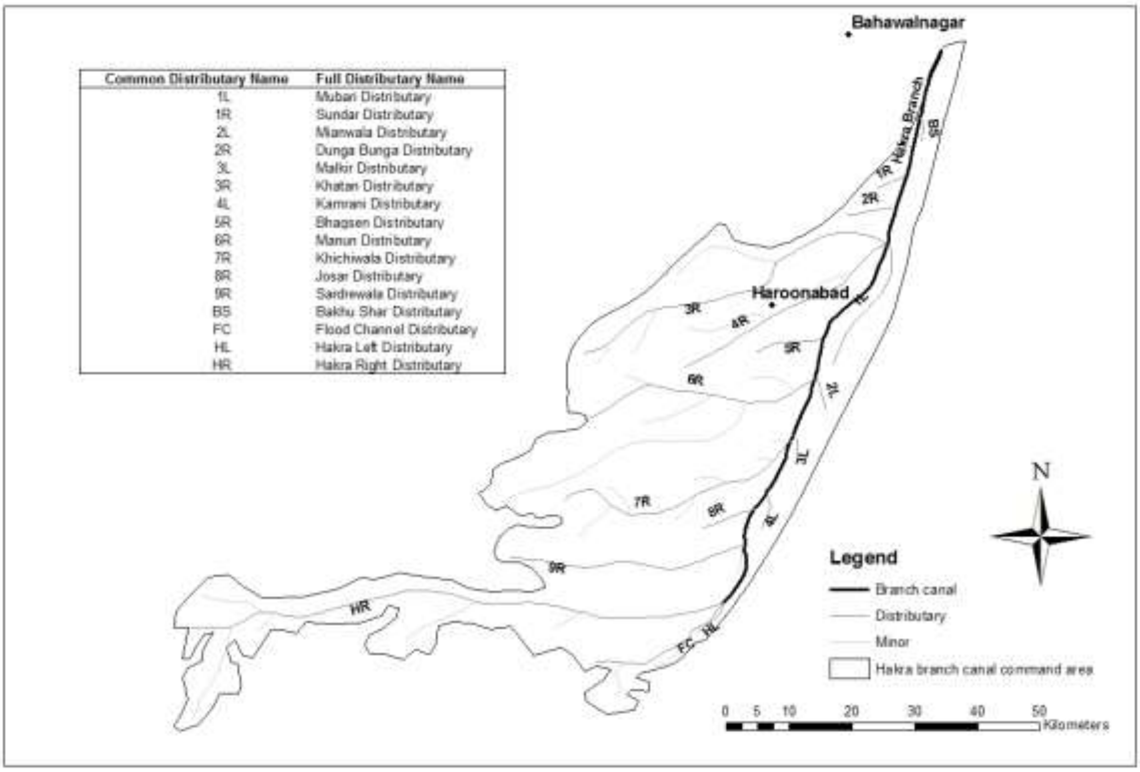


Figure 2-1 HBC and its distributaries (adapted from IWMI-Pak)

2.3.1. Sample site

a. Climate

The sample site, Hakra 5R command area, is served by Bhagsen distributary, commonly referred to as Hakra-5R distributary (Programe Monitoring And Implementation Unit (PIMU), 2015). It has a command area of 4,270 ha (De Vries, 2014). This area was selected to be a representative of the HBC command area because the climatic conditions, the physical conditions and various farming activities are reflective of the whole area. From literature (Kahlown et al., 1998; Naz, 2010; A. Qureshi, 2014; A. S. Qureshi et al., 2003) the HBC command area is classified as flat land hence, there is no orographic climate effect, no major rivers nearby and no significant difference in cropping pattern.

The climate of the area is characterized by large seasonal variability in temperature and precipitation. Table 2-1 shows the record summary of mean climatic conditions from Bahawalnagar Metrological Station, 50 kilometres from the HBC command area and spans over 31 years (1979-2010).

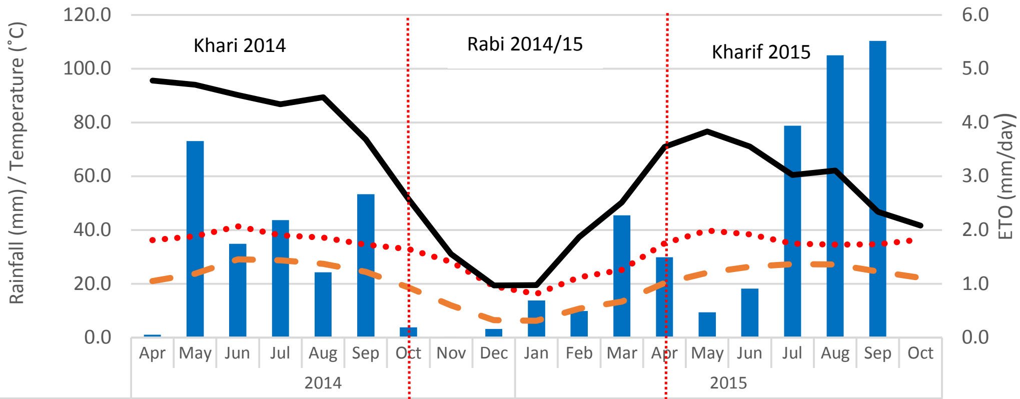
Table 2-1 Climatic conditions of the study area (1979-2010).

Description	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Mean Daily Min. Temp (˚C)	6.5	9.5	14.6	20.7	25.5	28.2	28.4	27.7	24.7	19.5	12.7	7.8	18.8
Mean Daily Max. Temp (˚C)	20.1	23.3	28.7	36.4	41.3	42	38.9	37.8	36.7	34.4	28.3	22.3	32.5
Humidity (%)	46.4	41.4	31.7	18.6	15.7	19.9	34.6	37.2	31.5	24.4	30.8	41.6	31.2
Mean Daily Wind speed (m/s)	0.7	1.0	2.6	2.7	2.7	2.9	2.9	2.8	2.5	2.1	2.0	1.4	2.2
Mean daily sunshine hours (MJ/m^2/day)	11.1	14.3	20	24.3	26.6	26.3	21.2	20	20.2	18.4	14.8	11.8	19.1
Mean Daily Rainfall(mm/day)	0.4	0.6	0.5	0.4	0.5	1.3	2.3	1.1	0.5	0.3	0.1	0.1	0.70
Mean daily ET$_O$ (mm/day)	2.5	3.6	5.2	7.2	8.5	8.8	7.3	6.7	6.1	4.8	3.4	2.6	5.6
Rainfall deficit (mm/day)	-2.1	-3.0	-4.7	-6.9	-8.0	-7.5	-5.0	-5.6	-5.6	-4.6	-3.3	-2.5	-4.9

Source: Pakistan Metrological Department Regional Office, Lahore

This area is characterised by hot summer and mild winter seasons (Kahlown et al., 1998). Based on the mean minimum and maximum temperature, January is the coldest month of the year while June is the hottest month over the period of 31 years. The precipitation in the area is generally scarce and intermittent and hence not a reliable source of crop moisture. June, July and August receive the bulk of the rainfall but are still hot and relatively dry while October, November and December are the driest. Rainfall deficit (crop water requirement), calculated as the difference between the mean daily rainfall and mean daily reference ET$_O$, ranges between 2.1 mm/day and 8 mm/day. The maximum rate of evapotranspiration occurs in the months of May, June and July with values of 8.5, 8.8 and 7.3 mm/day (De Vries, 2014; Kahlown et al., 1998).

Daily meteorological data recorded at IWMI Haroonabad office metrological station is stored in Hakra Farmer Organisation (Hakra FOSQL) database (maintained by IWMI-Pak) offers a better representation of the climatic conditions of the study area. The data acquired from the database run from April 17 2014 to October 9 2015 to make up for three complete growing seasons (Kharif 2014, Rabi 2014-15 and Kharif 2015) and is presented in Figure 2-2.



	Apr 2014	May 2014	Jun 2014	Jul 2014	Aug 2014	Sep 2014	Oct 2014	Nov 2014	Dec 2014	Jan 2015	Feb 2015	Mar 2015	Apr 2015	May 2015	Jun 2015	Jul 2015	Aug 2015	Sep 2015	Oct 2015
Total Rainfall (mm)	1.0	73.1	34.9	43.7	24.2	53.3	3.8	0.3	3.2	13.8	9.9	45.5	29.9	9.4	18.2	78.8	105.0	110.3	0.1
Mean Tmax (˚C)	36.3	37.6	41.3	38.1	37.1	34.5	32.8	28.1	19.0	16.3	22.5	25.1	35.1	39.7	38.3	35.0	34.5	34.6	36.5
Mean Tmin (˚C)	21.0	23.7	29.0	28.7	27.4	24.4	18.7	11.9	6.5	6.2	10.8	13.3	20.2	24.0	26.4	27.3	27.1	24.5	22.2
Mean monthly ETO	4.8	4.7	4.5	4.3	4.5	3.7	2.6	1.6	1.0	1.0	1.9	2.5	3.5	3.8	3.6	3.0	3.1	2.3	2.1

Figure 2-2 Meteorological data for Kharif 2014, Rabi2014/2015 and Khari 2015

The data presented in Figure 2-2 agrees with the long term data from Bahawalnagar Metrological Station. Kharif is characterised by high rates of evapotranspiration, temperatures and rainfall while Rabi is characterised by low rates of evapotranspiration, temperature and rainfall. Daily data shows that there is a marked reduction of daily evapotranspiration rates whenever it rains in Kharif. Rabi experiences dense fog, hence low rate of evapotranspiration (Naz, 2010). The total rainfall received in both Kharif seasons (230.2 mm in 2014 and 324.4 mm in 2015) is also higher than what was received in Rabi (103 mm). There is also a distinct temperature variation between Kharif and Rabi. Highest recorded temperature across the three season was 43˚C (Kharif 2014) while the lowest was 1˚C in Rabi 2014/2015.

b. Soils and Groundwater occurrence

According to Kahlown et al. (1998), the soils of this site are composed of alluvial materials eroded from the Himalayan ranges by the Sutlej and Hakra tributaries of the IBIS. There is a varied and mixed soil pattern throughout the area due to frequent changes in river flowrates, recurrent flooding and ponding of sediment laden waters. The parent material of the soils in this site is of mixed mineralogical composition. The soils are reddish brown to greyish brown, moderately coarse and medium textured, with a high percentage of fine to very fine sand and silt. The texture ranges between sand and clay with silt loams/ very fine sandy loams dominating recent flood plains while there is a hint of sand in the shallow depths. Areas under perennial/seasonal irrigation are dominated by loamy soils while the clays found in this site consists non swelling minerals. The soil map of HBC command area is shown in Figure 2-3.

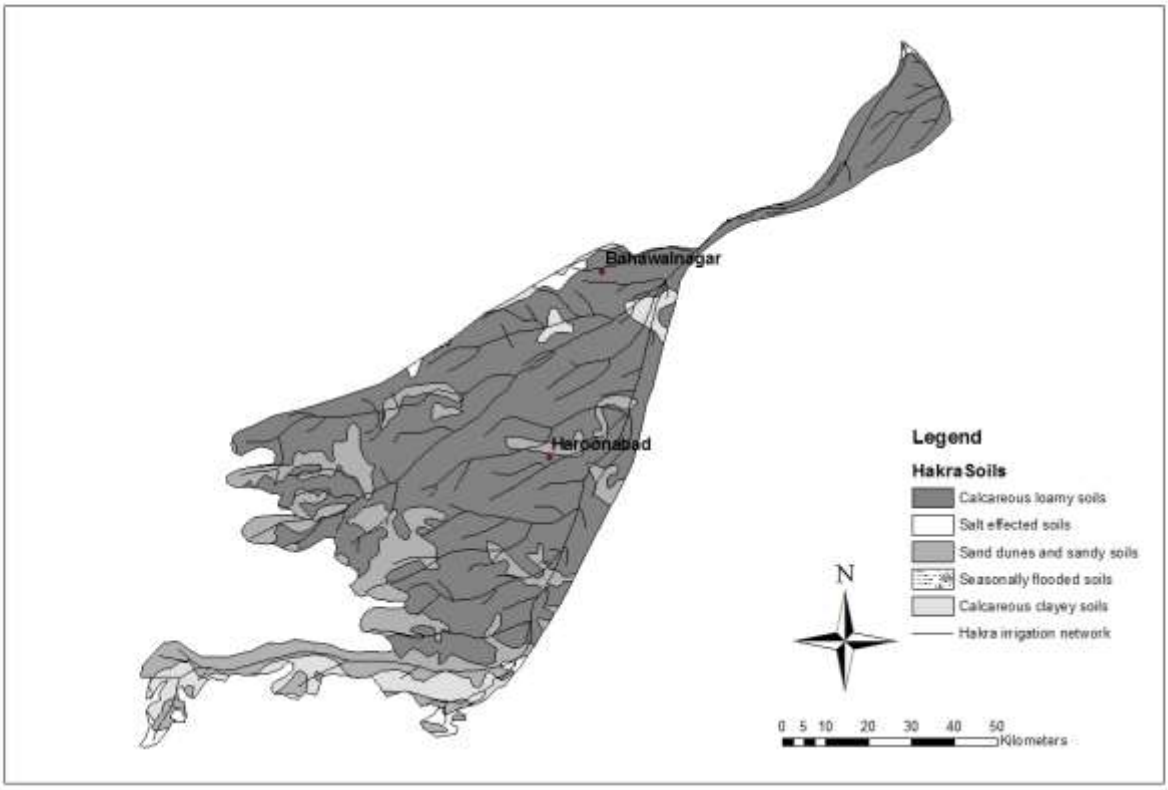


Figure 2-3 Soil map of HBC command area (adapted from IWMI-Pak)

Soil at the study site is silt loam as determined using physical soil classification conducted at the geotechnical laboratory of University of Engineering and Technology, Lahore. Table 2-2 shows the particle size distribution at different layers as tested following ASTM D422.

Table 2-2 Physical properties of the soil layers at various depths (data sourced from auger pits sampled in Hakra 6R on 12/2/2014)

		Particle size distribution	
Depth (cm)	**Gravel %**	**Sand %**	**Silt and Clay %**
0-30	0	39	61
30-60	0	42	58
60-90	0	44	56
90-120	4	46	50

The soils in this area are naturally fertile with a high potential for productivity but due to intensive farming carried out, organic matter and plant nutrients (such as nitrogen and phosphorous) are on the verge of depletion (Kahlown et al., 1998). Application of manure and/ or chemical fertilizers is carried out to try and correct nutrient depletion so that farmers can attain good yields (De Vries, 2000; Kahlown et al., 1998).

The soils have also been reported to have intrinsic salinity due to soil forming processes while the quality of groundwater in the shallow water table has been reported as saline (Condom et al., 1999; Condon et al., 2014; A. S. Qureshi et al., 2008). There are nine groundwater observation wells (GOW1 – GOW-9) installed by IWMI in the Hakra 5R distributary as shown in Figure 2-4. These wells monitor groundwater temperature, depth and specific conductivity with the aim of determining the quality of groundwater.

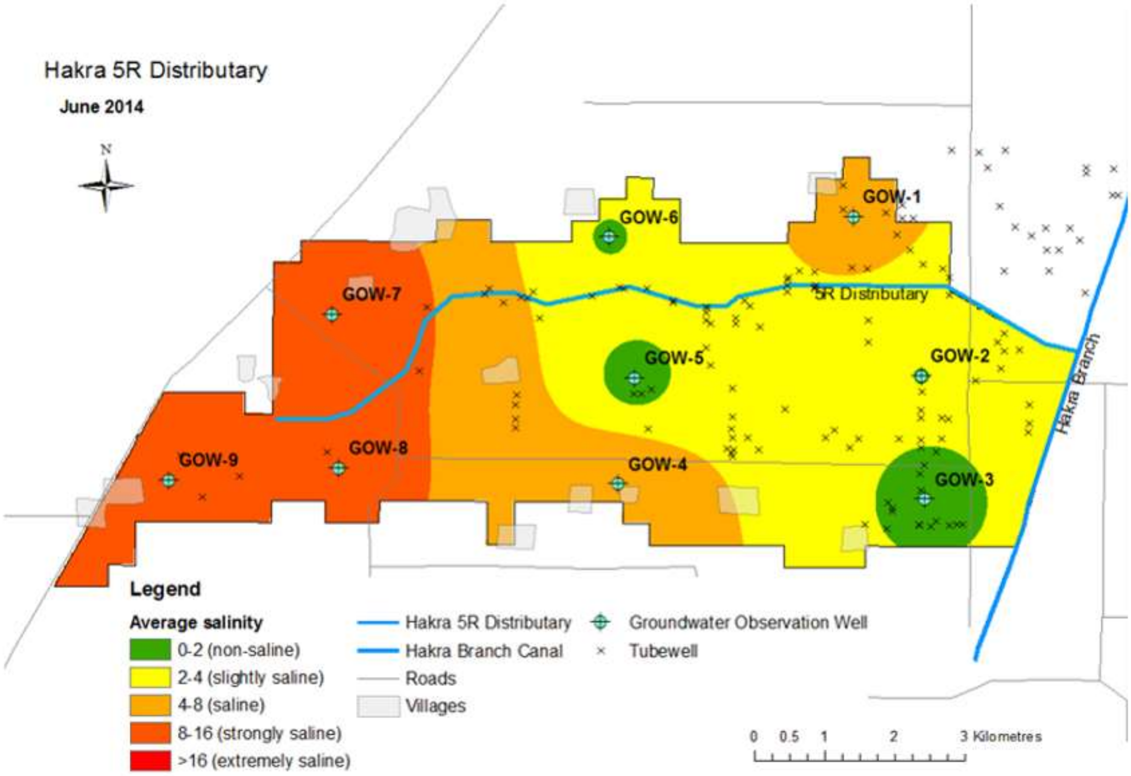


Figure 2-4 **Groundwater observation wells and corresponding salinity across the sample site (adapted from IWMI-Pak)**

Average daily groundwater level measurements across the nine wells do not indicate great variability with time but the level rose sharply between July and August 2015 probably due to local flooding as a result of excessive rainfall as shown in Figure 2-5. Data collected from the monitoring wells shows that the groundwater table lies between 0.002-3.5 m below the soil surface depending on the prevailing weather conditions.

The specific conductivity of the groundwater in the shallow water tables is also of interest in this study. It is the measure of dissolved inorganic solids such as chlorides and nitrates anions or sodium, magnesium, calcium etc. ions in water. Therefore, specific conductivity can be used to as an indicator of how saline a water sample is (Kijne & Kuper, 1995; Qureshi et al., 2008). If groundwater with high salinity is used for irrigation, either on its own or as a top up to surface flows, it might affect crops as they have different salinity tolerance. The specific conductivity of the groundwater shows great variation both in spatial and temporal terms and lies between 1.2 – 22 dS/m as illustrated in Figure 2-6.

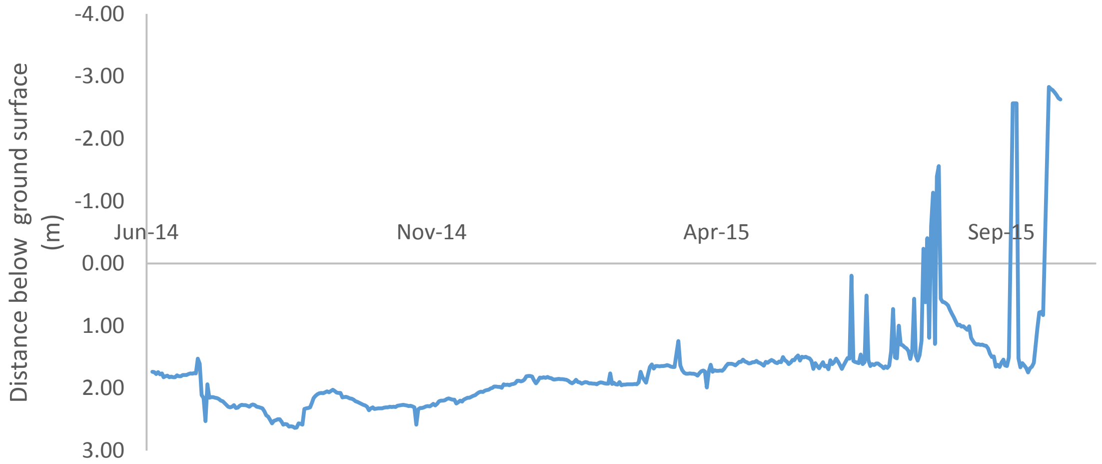


Figure 2-5 Level of groundwater table

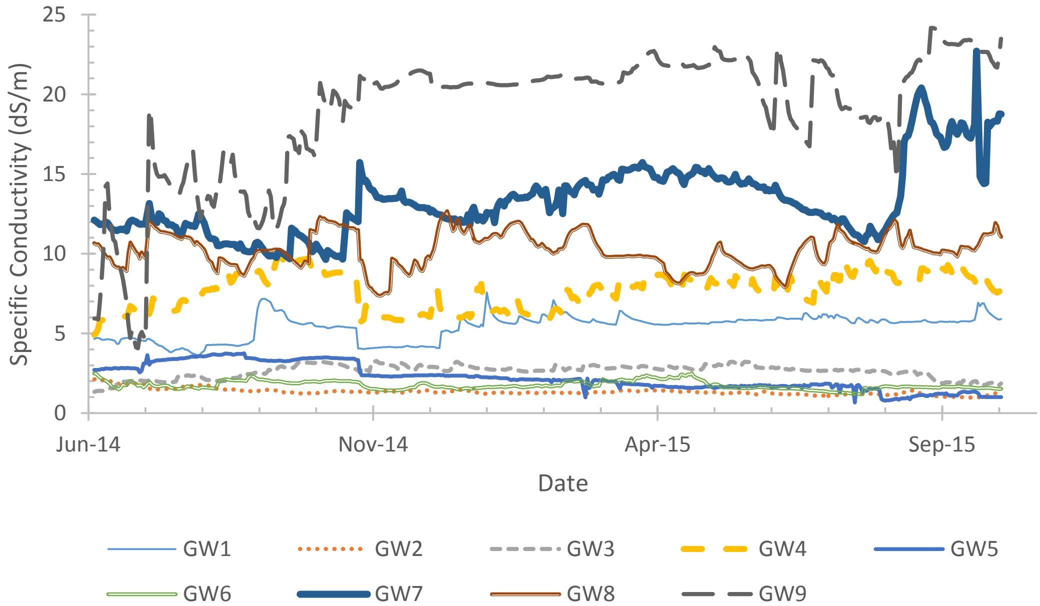


Figure 2-6 Spatial and temporal variation in groundwater specific conductivity

This means that the groundwater in the shallow water tables ranges from slightly saline to highly saline according to classification shown in Table 2-3. If this water is supplied to the crops, either by surface irrigation (from tubewells) or via capillary rise, it may lead to build up of salts in the root zone if there is no enough water to leach out the excess salts.

Table 2-3 Classification of saline water

Water Class	Electrical conductivity (dS/m)	Type of water
Non-saline	<0.7	Drinking and irrigation water
Slightly saline	0.7-2	Irrigation water
Moderately saline	2-10	Primary drainage water and groundwater
Highly saline	10-25	Secondary drainage water and groundwater
Very saline	25-45	Very saline groundwater
Brine	>45	Seawater

Source: (Rhoades et al., 1992)

Studies conducted by George & Hazlewood (2015) concluded that the variation in specific conductivity of the groundwater across Hakra 5R distributary had no clear trend and each of the monitoring well were independent of each other. The variation was concluded to be as a result of:

- Proximity of the monitoring well to the branch canal and/or distributary;
- Hydraulic characteristics of the channels leading to infiltration;
- Flow direction of water seeping from the channels assumed to have low specific conductivity;
- Number of tubewells within a 1 km and 500m radius intercepting fresh flows.

c. Irrigation and Crops

Rainfall deficit experienced in the HBC command area (between 2 and 8 mm/day) means that for crop production to make economic sense, irrigation is necessary. Extensive irrigation is carried out in this area and generally any irrigable area in Pakistan. The main irrigation method is surface irrigation via bed and furrow irrigation method which evolved from basin irrigation method (De Vries, 2000; Kalwij et al., 1999). The major crops cultivated under irrigation are cotton, wheat, rice and sugarcane under any of the following crop rotation pattern (Kahlown et al., 1998):

- Cotton-wheat-cotton;
- Rice wheat rice;
- Rice-wheat-cotton;
- Rice-berseem-rice-wheat;
- Kharif fodder-wheat-cotton;
- Sugarcane-wheat-cotton.

Land use map for the HBC command area is shown in Figure 2-7.

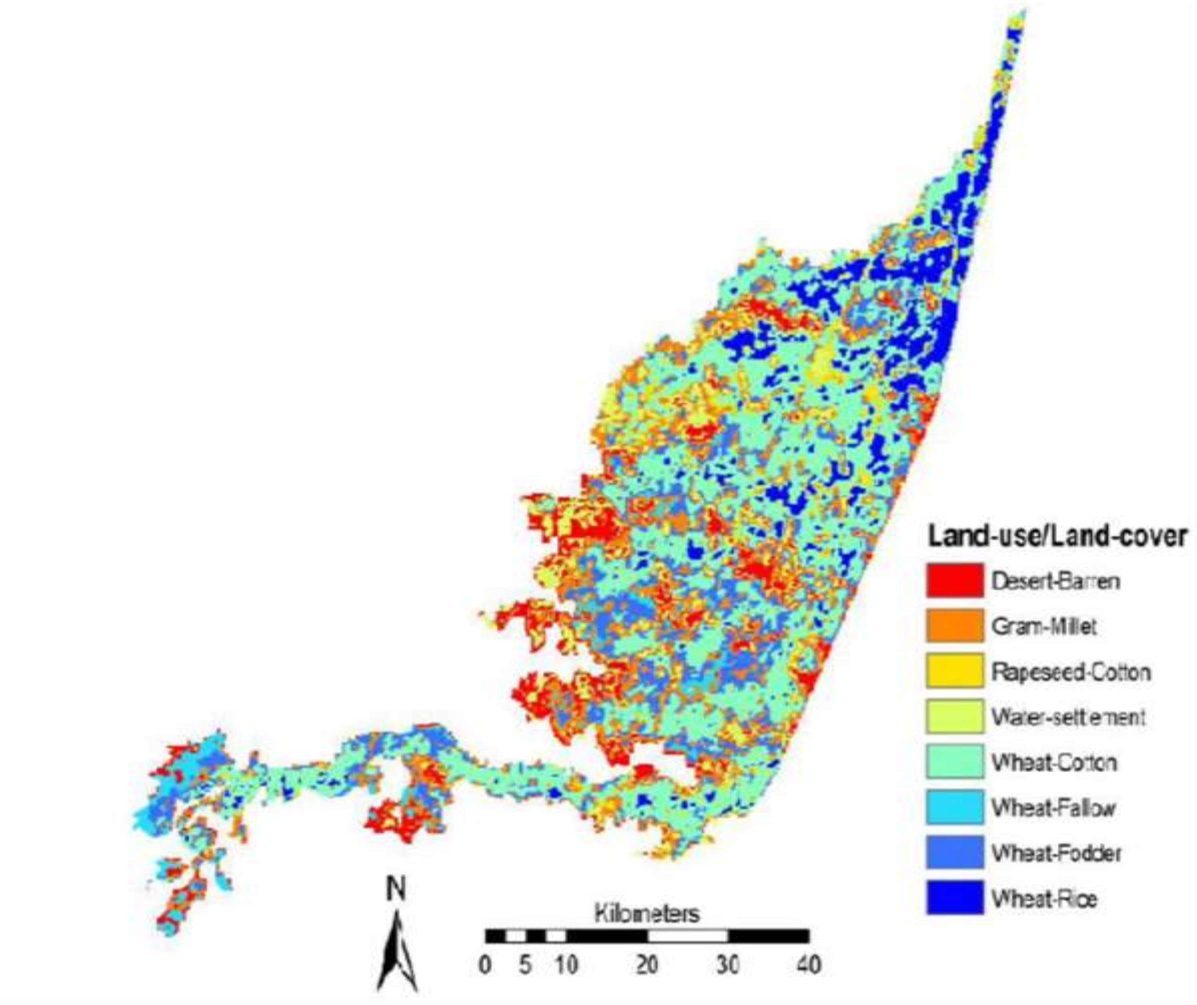


Figure 2-7 Land use map for HBC command area (adapted from IWMI-Pak)

2.4. Methodology

2.4.1. Method

In order to achieve the objectives of this research, different planting dates are selected based on the range that is usually adopted by the farmers. These dates are then combined with the three scheduling scenarios, in order to capture how the dates and schedules combine to affect achievable yield, amount of conjunctive water used, root zone depletion and accumulation of salts in the root zone at the end of a growing season. The different combinations are presented in Table 2-4.

Table 2-4 Combination of planting dates and scheduling scenarios and targeted outputs

Planting date	Scenario	Yield	Surface flows	GW	CR	Total water used	Depletion	Net salt accumulation
Date 1	PID A I							
Date 2	PID A I							
Date 3	PID A I							
Date 4	PID A I							
Date 5	PID A I							

The planting dates are selected to coincide with the start of Warabandi (when surface supply is scheduled to occur) and a gap is provided to capture variation in weather conditions. This is to ensure that the soils have enough moisture of high quality to support imbibition by the seeds. Cotton seeds, for example, are sensitive to saline water during germination. Surface flows are of high quality and would therefore be preferred to tubewell water when planting. The ECWA scheduling scenarios, Scenario A and I, have been selected according to their Gini indices while the current scheduling scenario (PID schedules) has been incorporated to show the current situation.

A crop water productivity model will be used to investigate how the different combinations of planting dates and scheduling scenarios as shown in Table 2-4 affect achievable yield, amount of conjunctive water used, root zone depletion and the accumulation of salts in the root zone at the end of the growing season. These scenarios will be applied on all the 17 distributaries separately and their results averaged since the schedules are applied across the HBC command area. The scenarios are capable of addressing the different objectives. A comparison of these outputs will be used to determine whether the ECWA schedules are better than the existing PID schedules.

Different crop models have been considered for their suitability in investing the combination of different planting dates and service interruption scheduling scenarios. AquaCrop version 4.0 has been selected for this research (see Section 3.1 for model selection criteria). The model and the required dataset are described in the subsequent sections.

2.4.2. Description of the AquaCrop

AquaCrop is a planning and management of irrigation decision support system developed by Land and Water Development Division of FAO (FAO, 2013a) .The model uses water as the main component in simulation of achievable yields of crops. Water is the main focus of the model because it is the key driver of agricultural production. There is increased pressure on the water as a result of growth in human population, industrialization and climate change. This makes water a critical resource in limiting crop production. The model performs the following tasks (FAO, 2013a; Steduto et al., 2012):

- Separates crop evapotranspiration (ET) into soil evaporation (E) and crop transpiration (T_r) to avoid the confusing effect of the non-productive consumptive use of water (E). This ensures that the water lost through soil evaporation (E), especially in the early stages when canopy cover of the ground is little, is not ignored as it make the major component of water lost from the soil when calculating biomass;
- Develops a simple canopy growth and senescence model as a basis for the estimate of TR and its separation from E;
- Treats the final yield (Y) as a function of final biomass (B) and harvest index (HI);
- Segregates the effects of water stress into four components – canopy growth, canopy senescence, T_r and HI.

Equation (2.1) is the engine of the model and shows how AquaCrop connects crop yields and crop water use;

$$B = WP \times \sum T_r \tag{2.1}$$

Where B is the cumulative biomass (kgm^{-2}), T_r is crop transpiration (mm or m^3 per unit surface) with the summation over the time period in which the biomass is produced and WP is the water productivity parameter in kg of biomass per m^2 and per mm, or biomass per m^3 of water transpired. WP parameter tends to be constant under given climatic conditions (Steduto, Hsiao, et al., 2009)

The model has a structure that assembles the soil-crop-atmosphere continuum by including the soil, with its water balance; the crop, with its growth, development, and yield processes and the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Some management actions (irrigation, fertilization, soil budding and mulching) are also considered as they affect soil fertility, crop development, water productivity and crop changes due to stress and therefore final yield changes (Steduto, Hsiao, et al., 2009; Steduto, Raes, et al., 2009). Figure 2-8 shows main components of soil-plant-atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. Continuous lines represent direct links between variables and processes while the dotted indicate feedbacks. Symbol are identified as: I, irrigation; T_n, minimum air temperature; T_x, maximum air temperature; ET_o, reference evapotranspiration; E, soil evaporation; T_r, canopy transpiration; g_s, stomatal conductance; WP; water productivity; HI, harvest index; CO_2, atmospheric carbon dioxide concentration; (1), (2), (3), (4), water stress response functions for leaf senescence, stomatal conductance and harvest index (Steduto, Raes, et al., 2009).

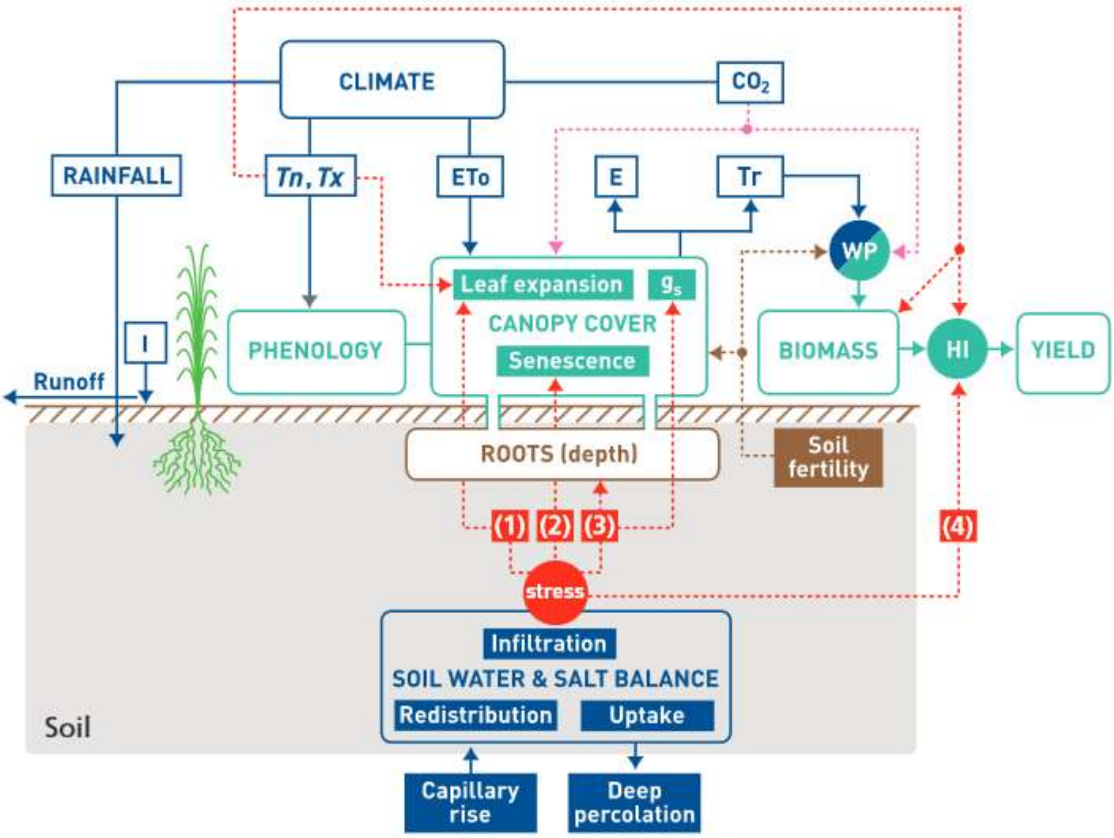


Figure 2-8 Main components of soil-plant-atmosphere continuum (Steduto et al., 2012)

The model consists of four components: soil, crop, atmosphere and management which are explained below (Steduto et al., 2012; Steduto, Hsiao, et al., 2009; Steduto, Raes, et al., 2009).

a. Soil

The soil component in the model is defined by a soil profile and characteristics of the groundwater table if present. The model allows the user to subdivide the profile vertically up to five layers of variable depths and soil physical characteristics (texture). Soil hydraulic characteristic included in the

model are field capacity (FC), permanent wilting point (PWP), drainage coefficient (τ) and hydraulic conductivity at saturation (K_{sat}). These soil parameters are derived from textural classes in the United State Department of Agriculture (USDA) triangle but if they vary significantly, the user can key them in (Raes et al., 2009b). The model uses these parameters to derive other parameters that govern soil evaporation, internal drainage, deep percolation, surface runoff and capillary rise. Groundwater table depth and salinity are the only groundwater characteristics that the model considers. These characteristics can remain constant or vary throughout the simulation period (Steduto et al., 2012).
The model is able to calculate the amount of water and salts retained in the root zone by keeping track of the incoming water (rainfall, irrigation and capillary rise) and outgoing water (deep percolation, evapotranspiration and runoff) and salt fluxes at the boundary of the root zone (Figure 2-9). This is made possible by combination of two subroutines, BUDGET (Raes et al., 2001) and UPFLOW (Raes & Deproost, 2003). BUDGET subroutine deals with infiltration, internal drainage, deep percolation, surface runoff, evaporation and transpiration while UPFLOW subroutine estimates the upward movement of water from shallow water table into the root zone. Water that may enter the soil profile from seepage from earthen canals is not accounted for by the model.

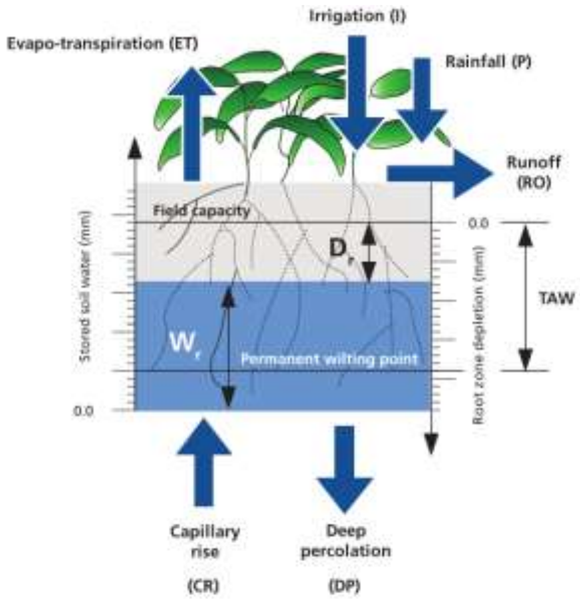


Figure 2-9 Water fluxes within the root zone reservoir (Steduto et al., 2012)

From Figure 2-9, the amount of water store in the root zone can be represented as an equivalent depth (W_r) or root zone depletion (D_r). At field capacity, D_r is zero while at permanent wilting point, D_r is equal to total available water (TAW).

Salt balance is also performed as the model performs water balance. Salts enter the root zone via capillary rise from saline groundwater table, in irrigation water or in commercial fertilizers and are leached out by excessive irrigation or rainfall. Fluxes in water and salts at the boundaries of the root zone can be calculated by budgeting the incoming water (irrigation, capillary rise and rainfall) and outgoing water (runoff, evapotranspiration and deep percolation), and then accounting for their salinity. BUDGET subroutine is responsible for simulating salt introduced through irrigation and fertilizer use while UPFLOW subroutine estimates the amount of salt introduced into the root zone through capillary rise (Steduto et al., 2012).

b. **Crop**

The crop module is made up of phenology, canopy cover, rooting depth, crop transpiration, soil evaporation, biomass production and harvestable yield (Steduto, Hsiao, et al., 2009). Over a crop's growth cycle, it develops by increasing its canopy and by expanding and deepening its root system leading to maturity. The model uses harvest index (HI) to allocate the portion of biomass that will be harvested but ignores distributing the rest biomass into various crop organs. This is deliberately done to simplify the model and avoid dealing with complexity and uncertainties associated with the distribution process. Biomass of the crop is a representation of water transpired over the growth period as shown in equation (2.1). If there is water deficit at any time over the crop's growth cycle, it might affect Tr and hence biomass accumulation. The amount of biomass lost depends on timing (flowering), severity and duration of water stress. The harvestable part of biomass is represented by equation (2.2) (Steduto, Raes, et al., 2009)

$$Y = HI \times B \tag{2.2}$$

Where Y is the biomass partitioned to harvested organs, B is the cumulative biomass and HI is the ratio of yield to biomass.

Phenology

Phenology is determined by cultivar characteristics and temperature regimes. Cultivar characteristics are usually specified by the user but the model uses growing degrees days (GDD) to show the effects of thermal time on phenology on daily time steps. All crops except forage crops have the following key development stages; emergence, start of flowering (anthesis) or root/tuber/storage-stem initiation, time when maximum rooting depth is achieved, start of canopy senescence and physiological maturity. The crop is said to complete any of these stages when a given number of GDD have elapsed. GDD are calculated as shown follows (Steduto et al., 2012);

$$GDD = T_{avg} - T_{base} \tag{2.3}$$

Where T_{base} (base temperature) is the temperature below which crop development does not progress (˚C) and T_{avg} is the average air temperature (˚C).

Canopy development

Canopy cover (CC), through its expansion, ageing, conductance and senescence determines the amount of water transpired and therefore the biomass produced. The model expresses canopy development through CC instead of the traditional leaf area index (LAI). This simplifies simulation to the level of allowing the user to enter the actual values of CC, even if they are estimated visually. CC is also easily obtained via remote sensing either as input for the model or to check the simulated CC (Steduto et al., 2012).

Root development

Water uptake in the root zone is simulated by describing the effective rooting depth (Z_e) and water extraction pattern (Raes et al., 2009b). Z_e is defined as the soil depth at which root propagation is sufficient to allow significant crop water uptake. Rooting depth is a function of time and crop cultivar. The model assumes the minimum effective rooting depth (Z_n) to be between 0.2 and 0.3 m when calculating the water balance. Root development begins when half of the time required for crop emergence ($t_o/2$) has elapsed and continues deepening until maximum depth is achieved as illustrated by equation (2.4) (Raes et al., 2009b);

$$Z = Z_{ini} + (Z_x - Z_{ini}) \sqrt[n]{\frac{\left(t - \frac{t_o}{2}\right)}{\left(t_x - \frac{t_o}{2}\right)}} \tag{2.4}$$

Where Z is the effective rooting depth at time t (in days) after planting, Z_{ini} is the sowing depth, Z_x is the maximum rooting depth, t_o is the time from planting to effective (85-90%) emergence of the crop, t_x is the time after planting when Z_x is reached and n is the shape factor of the function. The unit of time is GDD. Figure 2-10 shows a generalised rooting depth development with time.

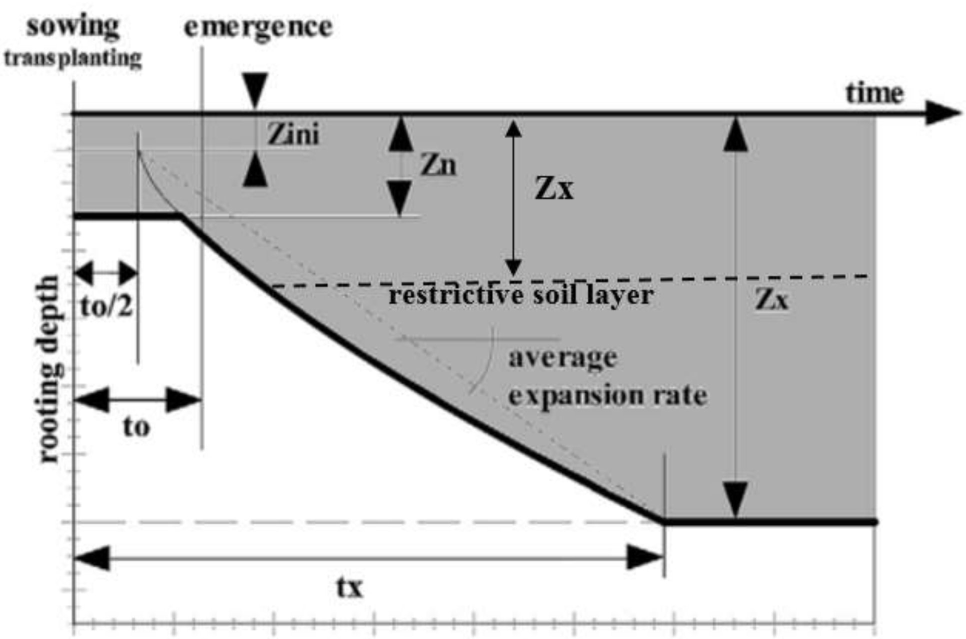


Figure 2-10 Generalised rooting depth development with time (Steduto, Hsiao, et al., 2009)

Z_x is expected to be achieved near the end of the crop's life cycle; around the start of canopy senescence which depends on presence or absence of soil restrictions (restricting soil layer or shallow groundwater table). Z_n represents minimum effective rooting depth in metres.

Crop transpiration

Transpiration, T_r, depends upon the fraction of soil covered by canopy (CC) in absence of stresses that would interfere with stomatal opening but the dependence is not linear due to interference from inter-row micro-advection and the shielding effect of incomplete CC (Steduto, Hsiao, et al., 2009). The model compensates for the energy supplied from micro-advection by assuming a larger effective cover denoted by CC*. The relationship between T_r and CC* is given by equation (2.5) (Steduto, Hsiao, et al., 2009);

$$T_r = K_{cb} ET_o \tag{2.5}$$

With

$$K_{cb} = CC^* \times K_{cbx} \tag{2.6}$$

Where K_{cbx} = crop coefficient when CC is fully developed

Transpiration and photosynthetic capacity of the green portion of the canopy starts to slow down when maximum CC is achieved and they drop significantly when senescence is triggered.

Water stress is identified by the model through any of the three thresholds; for leaf growth, for stomatal conductance and for acceleration of senescence (Steduto et al., 2012). Transpiration is reduced when any of these threshold is reached before the crop reaches maturity. Water logging is also considered as a factor that affects growth by way of affecting aeration in the root zone.

Soil evaporation

Soil evaporation, E, takes place on wet surfaces that are not covered by the canopy. E will be higher when the canopy is little but will reduce as the CC increases. Wetness of the soil surface is the other key factor that drives the way the model handles E. E proceeds at about 10% more than the rate of ET_O when the soil surface is fully wet and falls off exponentially with decline of water in the top soil (Steduto et al., 2012).

Biomass production

The biomass water productivity (WP) is the main driver of the model as indicated in Equation (2.1) and it has been shown to remain relatively constant when normalised for different evaporative demands. The WP parameter in the model is normalised for the atmospheric environment of the crop (climatic conditions and carbon dioxide concentration). The normalised biomass water productivity (WP*) has been investigated thoroughly and has been shown to remain nearly constant for a given crop if there are no limiting factors, for example, mineral nutrients irrespective of water stress; except in extreme cases (Steduto et al., 2007). However, WP* has been seen to spike slightly in instances where higher CO_2 concentration in the air has been detected. Due to this spike, the WP* is calibrated so that it is unique for each crop and it is applicable in all climatic scenarios (past, present and future) as shown in Equation (2.7) (Steduto et al., 2012).

$$WP^* = \left[\frac{B}{\sum \frac{Tr}{ET_o}}\right]_{[CO_2]} \tag{2.7}$$

Where summation indicates the time interval when B is produced, CO_2 outside the brackets indicates that the normalised value is for a particular air carbon dioxide concentration.

Equation (2.7) can only be used directly when the values of ET_O and T_r are available for daily time intervals, otherwise the modeller needs to approach the normalisation process cautiously.

Harvestable Yield

Yield, Y, is calculated using Equation (2.2). The HI is zero at the start of flowering, lagging over a short period until it linearly increases until it stops sharply as the crop nears physiological maturity as shown in Figure 2-11 (Steduto et al., 2012).

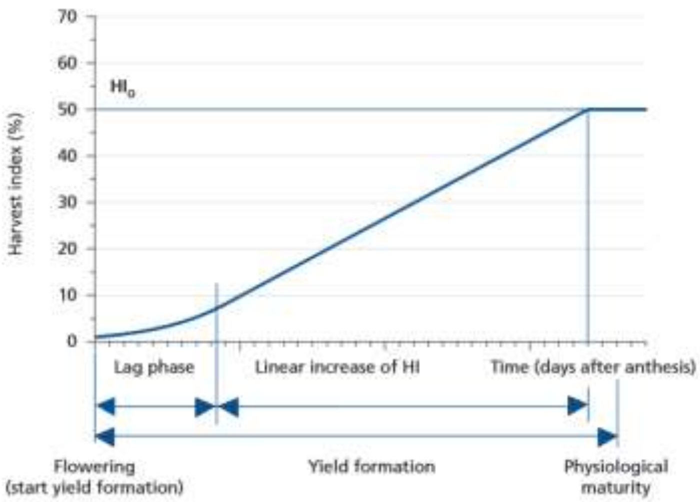


Figure 2-11 Building up of HI from flowering to maturity for fruit and grain (Steduto et al., 2012)

c. Atmosphere

The atmospheric environment of the model is described by the climate component by four daily weather variables (Steduto, Hsiao, et al., 2009; Steduto, Raes, et al., 2009):

- Maximum and minimum air temperatures (T_x and T_n);
- Rainfall;
- Evaporative demand expressed as ET_O. AquaCrop model is not able to calculate ET_O internally but has an accompanying model known as ET_O calculator for this purpose;
- Annual mean CO_2.

Temperature has direct effect on crop development and when limiting (too high or too low), it affects biomass accumulation and pollination (hence HI). Rainfall, irrigation and ET_O are used to calculate the water balance in the root zone and water stress while CO_2 concentration affects WP, CC and stomatal conductance.

T_x, T_n, ET_O and rainfall are entered into the model and are usually derived from agrometeorological weather stations but the model uses default CO_2 values obtained from Manua Loa observatory in

Hawaii (Steduto, Hsiao, et al., 2009). This is attributed to the fact that CO_2 variations are small and have minimal impact on crops.

d. Management

Management module is divided into two categories: field management and water (irrigation) management.

For field management option, it is possible to choose or define:

- Fertility level of the field (natural or by fertilization);
- Soil surface treatment (mulching to reduce soil evaporation or use of soil bunds to regulate surface runoff and enhance infiltration);
- Harvesting time for forage crops.

For water management option, it is possible to choose or define whether the enterprise is rainfed (no irrigation) or irrigated. Under irrigation, it is possible to select the mode of application (sprinkler, drip or surface) and define the irrigation schedule by specifying time and depth of application.

The model has a capability of automatically generating a schedule based on fixed time interval, fixed depth per application or fixed percentage of allowable water depletion. It also calculates the full water requirement of the crop from the climatic data supplied (Steduto, Raes, et al., 2009).

2.4.3. AquaCrop Inputs

The datasets required for the model to run are divided into two major classes; environmental and crop data and simulation data as shown in Table 2-5 (Steduto, Hsiao, et al., 2009) ;

Table 2-5 Input data required for AquaCrop model

Main parameter	Sub parameter	Information required
Environment and crop data	Climate	Daily/ 10 days/ monthly rainfall Daily/ 10 days/ monthly ETo Daily/ 10 days/ monthly temperature Carbon dioxide concentration
	Crop	Limited set, that is, crop development and production parameters which include phonology and lifecycle length Full/ all crop parameters, that is, evapotranspiration, water stress, air temperature stress and calendar of growing cycle.

Main parameter	Sub parameter	Information required
	Management	Irrigation type Field-soil fertility, mulches and field surface practices (soil bunds or surface runoff occurrence)
	Soil	Soil profile, that is, characteristic of soil horizon (number of horizons, thickness, PWP, FC, SAT, K_{sat}), soil surface (runoff and evaporation) capillary rise and occurrence of restrictive layer Groundwater characteristics, that is, constant or varying depth and the water quality (specific conductivity)
Simulation data	Simulation period	Linked to the growing season
	Initial conditions	Initial soil water content Soil layer thickness Soil salinity

Source : (Kumar et al., 2014; Steduto et al., 2012)

a. Meteorological data

Meteorological data was derived from the IWMI Haroonabad Office weather station, 8 km from Hakra 5R Distributary offtake. The weather station has been chosen as it is well equipped and managed by IWMI–Pak. The meteorological station is central within the study area as opposed to Bahawalnagar Metrological Station, which is about 50 km outside the project area, and therefore the Haroonabad Office station data is a better representative of the expected conditions of the farms. Hourly weather measurements of temperature, wind speed, direct solar radiation, precipitation, atmospheric pressure and relative humidity were downloaded from Hakra Farmer Organisation (Hakra FOSQL) database (maintained by IWMI-Pak) and aggregated to form daily weather data measurements. The data used runs from April 17 2014 to October 9 2015 to make up for three complete growing seasons: Kharif 2014, Rabi 2014-15 and Kharif 2015 (Appendix A)

Since AquaCrop does not have internal routines to calculate reference ET values, American Society of Civil Engineers (ASCE) standardised ET equation (Allen et al., 2005b) was used to calculate daily reference ET values. The equation is an improvement of ASCE Penman-Monteith because the computation procedures of different equation values are fixed. Equation (2.8) shows the standardised ET equation (Allen et al., 2005b);

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{2.8}$$

Where ET_{sz} is the standardized reference crop ET (mm d^{-1}); *Rn* is the calculated net radiation at the crop surface (MJ/ m^2/ d); *G* is the soil heat flux density at the soil surface (MJ/ m^2/ d); *T* is the mean hourly air temperature at 1.5 – 2.5m height (^{0}C); u_2 is the mean hourly wind speed at 2m height (m/s); e_s is the saturation vapour pressure at 1.5 to 2.5m height (kPa); e_a is the mean actual vapour pressure at 1.5 – 2.5m (kPa); Δ is the slope of the saturation vapour pressure-temperature curve (kPa/ ^{0}C); γ = psychrometric constant (kPa/ ^{0}C); C_n is the numerator constant dependent on reference crop type and calculation time step (K mm s^3/ Mg/ d); C_d is the denominator constant that changes with reference crop type and calculation time step (s/m); the units for the 0.408 coefficient are m^2 mm/ MJ and is used to convert units of energy to units of depth.

Equation (2.8) can be applied to both short reference crop evapotranspiration (ET_{os}) similar to grass and tall reference crop evapotranspiration (ET_{rs}) similar to alfalfa. Values for C_n and C_d are shown in Table 2-6. ET_{os} has been adopted for this research as it has been widely used by in the literature (Meerbach ,1997, Kahlown et al. ,1998 and Naheed & Rasul,2010b).

Table 2-6 Values for C_n and C_d

Calculation time step	Short reference, ET_{os}		Tall reference, ET_{rs}		Units for ET_{os}, ET_{rs}	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during night time	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Source : Allen et al. (2005b)

Procedures set out by Allen et al. (2005b) have been followed to calculate all components required for computation of daily ET values using Microsoft Excel™ spreadsheets.

The daily reference ET values calculated, together with the aggregated daily rainfall and daily maximum and minimum temperature values are converted into text files (.txt) suitable for AquaCrop to form the climate file. Carbon dioxide concentrations as recorded from Manua Loa Observatory, Hawaii are used (default values) since atmospheric variations of CO_2 in different locations are small and have insignificant impacts on crops (Steduto et al., 2012).

b. Crop data and management practices

AquaCrop presents two sets of crop parameters, that is, limited set and full set. Limited set parameters describe phenology and life cycle length of the crop while full set parameters describe crop parameters such as evapotranspiration, different types of stresses and growing calendar. To fully utilize the full set crop parameters, calibration of the model is necessary which has not been done in this study due to limited data availability. Therefore, limited set crop parameters are adopted. They are broadly divided into two groups; conservative/cultivar dependent and condition dependent parameters. Conservative parameters remain constant with time, management practices or geographical location while conditions dependent parameters vary with cultivars and conditions in which the crop is being grown, for example, life cycle length and phenology (Steduto et al., 2012).

Since model calibration has not been carried out, the conservative parameters are used as provided in the model with the exception of water use productivity function which has been adjusted according to the value derived from various studies in the region. Cotton has been adjusted according to Singh et al. (2006b) while wheat takes after studies carried out by Kahlown et al. (2007). The condition dependent parameter that adjusted to fit the environment is the planting density. Planting dates have been selected to reflect the farmers' practice derived through experience or from agricultural extension staff advice. The conservative and conditional parameters that have been adjusted are as shown in Table 2-7.

Table 2-7 Crop parameters adjusted to suit environment

Crop	Conservative parameter (Water productivity)	Condition parameter (Plant density)	Planting date
Cotton	0.23kg/m^3	10kg/ha	April to mid- June
Wheat	1.38kg/m^2	90kg/ha	Mid- Nov to end- December

Source : (Kahlown et al., 2007; Singh et al., 2006b)

Actual crop evapotranspiration at each growth stage (and hence crop water requirements) is determined by AquaCrop through the use the of daily soil water balance. The daily water balance method considers root zone as a reservoir into which water is supplied by rainfall, irrigation and capillary rise while evapotranspiration and drainage are responsible for extraction of water from this reservoir (Allen et al., 2005a).

c. Management

The management information required to run AquaCrop is described by the type of irrigation practices and the type of field management practices carried out on the farm. The model determines the crop water requirements based on climatic conditions and soil characteristics and then determines the appropriate schedules based on either fixed time intervals or on allowable depletion of readily available water. It is also possible to use schedules developed outside the model. The irrigation method applied in this research is surface irrigation (basin irrigation method) while the amount of water applied is as derived from ECWA model schedules (EC_e of 0.2 dS/m) (Appendix B) and from tubewells (EC_e of 2.45 dS/m).

The surface irrigation water is set to follow the Warabandi system (Appendix C), while the tubewell water is set to be supplied when the root zone depletion is at 50% of the readily available water (RAW). This is to ensure that the crop does not suffer excessive water stress.

Field management practices that affect how AquaCrop works include soil fertility, mulching, contour ploughing or ridging and building of soil bunds (Raes et al., 2009a). Mulches applied on the soil surface will affect the rate of soil evaporation while ploughing practices like ridging and contour ploughing eliminates rain-water runoff. Soil bunds acts as water stores on the field while soil fertility affects the rate of canopy cover (CC) development (and therefore crop transpiration) and biomass water productivity (WP*).

Reviewed of literature concluded that practices such as mulching, contour ploughing or ridging and construction of soil bunds are not practiced by farmers in the HBC command area. Soil fertility level adopted for the region is classified as "Near optimal" whose effect is about 24% on the crop yield. This was chosen in line with findings reported by Akram et al. (2014) stating that the soil fertility of the area is inherently low but decent crop yields can still be obtained by balanced use of inorganic fertilizers and application of manure to increase organic matter content in the soil.

d. Soil data

As seen in section 2.3, silt loam soils occupy most areas under irrigation in the HBC command area. AquaCrop has default settings on various soil physical characteristics which include soil water content at saturation, field capacity and permanent wilting point and saturated hydraulic conductivity (Steduto, Raes, et al., 2009) which are adopted for this research. Daily groundwater table depth and specific conductivity of the groundwater are obtained from Hakra Farmer Organisation database and then converted into text file (.txt) and uploaded into the model. There was no restrictive soil layer reported during auguring but the model is configured to assume that the depth of groundwater table will restrict further root development (Steduto, Raes, et al., 2009).

Reviewed of literature did not contain any information on the salinity profiles of the HBC command area. However, there were salinity profiles of two field studies carried out in Haryana State, India, at Karnal station (Sharma & Tyagi, 2004) and Sirsa district (Singh et al., 2006a). Haryana state has climatic conditions, irrigation practices and crops grown that are similar to HBC command area (Fujisaka et al., 1992) which made it an ideal site from which to adopt salinity profiles. Karnal station and Sirsa field sites are about 160 km from HBC command area. Sirsa district profiles were not used the soil classes were different from those at the study site. The salinity profile adopted from Karnal station is shown in Table 2-8.

Table 2-8 Initial soil salinity used

Depth (cm)	pH	EC_e
0-15	7.8	1.51
15-30	7.8	1.7
30-60	8	1.82
60-90	8.05	2.51
90-120	8.2	3.42

Source; (Sharma & Tyagi, 2004)

2.4.4. Analysis of Results

There are statistical indicators incorporated in the model to evaluate its performance. These indicators include coefficient of determination (R^2), root mean square error (RMSE), normalised room mean square error (NRMSE), Nash-Sutcliffe model efficiency coefficient (EF) and Willmott's index of agreement (d). R^2 denotes the magnitude of variance in measured data, RMSE denotes the average magnitude of the difference between prediction and observations, NRSME is percentage that shows the relative differences between observed and predictions, EF shows how well the plot of observed versus simulated data fits the 1:1 line while d measures the amount by which the observed data approaches the predicted data (Raes et al., 2009b).

Since there are no observed outputs in this research, the model statistical indicators or any other statistical indicators cannot be used in the analysis of results. This is because there no uncertainty as the input data for each simulation run is known. The only way to analyse the results is by direct interpretation of the differences between the outputs of interest, for example, difference between yield as a result of one planting date and the next.

CHAPTER 3: RESULTS AND DISCUSSION

3.1. Model selection decision criteria

Different models have been investigated for their suitability to output information on the crop- soil - water atmosphere in terms of achievable yield, available water use, salt accumulation and root zone depletion when provided with daily meteorological data. The models that have been studied include APSIM, AquaCrop, CropWat, CROPSYST DSSAT, STICS, SWAP, SWAT and WaSiM (Table 1-4). The indicators used to evaluate the suitability of the different models include soil water balance, pre-calibrated crops (crop information), irrigation management, data availability and relevant outputs (achievable yield, crop water utilisation, root zone depletion and salinity accumulation) as shown in Table 3-1.

Table 3-1 Model selection criteria

	Soil water balance	Pre-calibrated crops	Irrigation management	Data availability	Relevant outputs	Issues	Decision
APSIM	✓	✕	✓	✕	✓	• Cotton is not pre-calibrated; • Requires nitrate, nitrogen and residue data which is not available.	NO
AquaCrop	✓	✓	✓	✓	✓	• Data available and desired outputs achieved.	YES
CropWat	✓	✓	✓	✓	✓	• Superseded by AquaCrop; • Reports yield in terms of percentage.	NO
DSSAT	✓	✓	✓	✓	✕	• Does not have a salinity module; • Numerous data requirements.	NO
STICS	✓	✓	✓	✕	✓	• Requires genetic parameters since it is a generic model; • Requires nitrate, nitrogen and residue data which is not available; • Requires the soil's thermal regime which is not available.	NO
SWAP	✓	✓	✓	✕	✓	• Requires detailed hydraulic properties of the soil to define initial, upper and lower boundary conditions which is not available.	NO
SWAT	✓	✓	✓	✕	✓	• Numerous data requirements: hydrologic response units, land management practices, Nutrient and pesticide information, reach routing.	NO
WaSiM	✓	✓	✓	✓	✕	• Does not have a yield module.	NO

AquaCrop is the better choice for this research because its data requirements are not numerous and are easily available. The model has a strong emphasis on the processes involved in crop productivity and response to water availability, the outputs matches the objectives of the research and it is user friendly.

3.2. Crop Simulations

3.2.1. Effects of different planting dates and scheduling scenarios on achievable yield

This section presents the simulation results of achievable yield of cotton and wheat as dictated by different planting dates and scheduling scenarios. The results have been obtained by aggregating and averaging the achievable yield from all the 17 distributaries serving the HBC command area.

a. Cotton

Table 3-2 shows the simulated results of achievable yield for the various planting dates and scheduling scenarios for cotton. It can be seen that planting earlier in the season achieves better yields than planting late in the season regardless of the scheduling method used. PID and Scenario A schedules achieve the highest yield for the crop planted in Week 1 of Kharif 2014 while Scenario I has the highest yield for the crop planted in Week 3. This is also the highest yield achieved across the three scheduling scenarios.

Table 3-2 Simulated cotton yield for different planting dates and scheduling scenarios (cotton-Kharif 2014)

		Yield (Kg/ha)					
		PID		Scenario A		Scenario I	
Week Number	Planting date	Mean	Range	Mean	Range	Mean	Range
Week 1	17/04/2014	2,356	2,335-2,365	2,357	2,354-2,361	2,358	2,346-2,361
Week 3	01/05/2014	2,352	2,350-2,356	2,353	2,335-2,357	2,366	2,352-2,534
Week 5	15/05/2014	2,348	2,345-2,352	2,345	2,339-2,352	2,350	2,334-2,352
Week 8	05/06/2014	2,282	2,247-2,286	2,281	2,251-2,284	2,283	2,281-2,284
Week 10	19/06/2014	2,224	2,215-2,257	2,224	2,216-2,283	2,223	2,221-2,225

The difference in the achievable yield between scheduling scenarios planted on the same day is between 1 and 3 kg/ha except on Week 3 where Scenario I achieved 13kg/ha more than both PID and Scenario A. The differences in achievable yield between earliest planting date and subsequent dates selected are shown in Table 3-3. There is minimal difference (0.4%) in achievable yield for the crop planted during Week 3 and 5 but there was is difference (between 3.2 and 5.9%) for the crop planted in Week 8 and 10 compared to crop planted in Week 1.

Table 3-3 **Differences in achievable yield for different planting dates and scheduling scenarios compared to Week 1 (cotton - Kharif 2014)**

		Difference					
		PID		Scenario A		Scenario I	
Week number	Planting date	Kg/ha	%	Kg/ha	%	Kg/ha	%
Week 3	01/05/2014	4	0.2	4	0.2	8	0.4
Week 5	15/05/2014	8	0.4	8	0.4	8	0.4
Week 8	05/06/2014	74	3.2	76	3.2	75	3.2
Week 10	19/06/2014	132	5.8	133	5.8	135	5.9

Since farming is an economic activity, maximizing profit from agricultural production is paramount. Cotton planted early in the season usually fetches a better market price than cotton planted late in the season as reported by IndexMundi (2016a). Cotton crop planted in Week 1 and 3 would fetch US$ 0.074/kg higher than crop planted in Week 5, 8 and 10. Considering the HBC command area (200,000ha), the regional loss in both achievable yield and revenue as a result of planting in Week 8 and 10 (since there is minimal difference in yield between Week 1, 3 and 5) is shown in Table 3-4. For example, shifting the planting date from Week 10 to Week 1 under Scenario I scheduling would bring an extra revenue of about US$ 2 million.

Table 3-4 **Yield and revenue forgone for cotton as a result of planting late in the season for the entire HBC (Kharif 2014)**

Scheduling Scenario	Yield forgone (tonnes)		Revenue forgone (US $)	
	Planting in Week 8	Planting in Week 10	Planting in Week 8	Planting in Week 10
PID	14,800	26,400	1,100,582	1,963,200
Scenario A	15,200	26,600	1,130,327	1,978,072
Scenario I	15,000	27,000	1,115,454	2,007,818

For Kharif 2015, only one planting date has been selected as more data which would have allowed for selection of a variety of planting dates was not available at the time of analysis. The selected date is 16/04/2015 and represents Week 1 of Kharif 2015. The achievable yield for this week is shown in Table 3-5. There is a minimal difference in the achievable yield across the three scenarios of scheduling. This is in agreement with the results achieved for cotton crop planted in Week 1 of Kharif 2014. The difference in achievable yield between the different scheduling scenarios for the two seasons was 6 kg/ha, 5kg/ha and 3 kg/ ha for PID, Scenario A and I respectively, with Kharif 2015 being the better season. This represents a minimal difference between seasons and hence, it is expected that the same trend in achievable yield witnessed in Kharif 2014 will continue in Kharif 2015.

Table 3-5 Simulated cotton yield for different scheduling scenarios (Kharif 2015)

Scheduling Scenario	Yield (Kg/ha)
PID	2,362
Scenario A	2,362
Scenario I	2,361

b. Wheat

Table 3-6 shows the simulated results of achievable yield for the various planting dates and scheduling scenarios for wheat averaged for all the 17 distributaries serving the HBC command area Earlier planting dates, as with cotton, achieves better yield than planting late in the season regardless of the scheduling method. Wheat crop planted in Week 5 of Rabi 2014/2015 achieves the highest yield (3,764 kg/ha) while that planted in Week 10 achieves the lowest yield (2,867 kg/ha). Week 11's crop performed better than Week 10's crop by 84 kg/ha, 87 kg/ha and 51 kg/ha for PID, Scenario A and I respectively. The range between the lowest and the highest yield achieved is the same for all the scheduling scenarios.

Table 3-6 Simulated wheat yield for different planting dates and scheduling scenarios

		Yield (Kg/ha)					
Week Number	Planting date	PID		Scenario A		Scenario I	
		Mean	Range	Mean	Range	Mean	Range
Week 5	13/11/2014	3,764	3,740-3,771	3,764	3,740-3,771	3,764	3,740-3,771
Week 7	27/11/2014	3,385	3,362-3,395	3,385	3,362-3,395	3,385	3,362-3,395
Week 9	11/12/2014	3,075	3,052-3,086	3,075	3,052-3,086	3,075	3,052-3,086
Week 10	18/12/2014	2,867	2,852-2,877	2,867	2,852-2,877	2,867	2,852-2,877
Week 11	25/12/2014	2,951	2,939-2,966	2,954	2,939-2,966	2,918	2,939-2,966

There is no difference in achievable yield between scheduling scenarios for crop planted in the same day except in Week 10 where Scenario I achieves 33kg/ha and 36kg/ha lower than PID and Scenario A schedules The differences in achievable yield between the earliest planting date (best yields) and subsequent selected planting dates are shown in Table 3-7. There is a substantial reduction in achievable yield as the planting date selected deviates further from beginning of Rabi 2014/15 despite the crop experiencing less temperature stress for the latter dates. Wheat crop planted in Week 5 and 7 experiences 7% temperature stress, crop planted in Week 9 experiences 4% temperature stress while that planted in Week 10 and 11 experiences 2% temperature stress.

Table 3-7 Differences in achievable yield for different planting dates and scheduling scenarios compared to Week 5 (wheat-Rabi 2014/2015)

		Difference					
		PID		Scenario A		Scenario I	
Week Number	Planting date	Kg/ha	%	Kg/ha	%	Kg/ha	%
Week 7	27/11/2014	379	11.2%	379	11.2%	379	11.2%
Week 9	11/12/2014	689	22.4%	689	22.4%	689	22.4%
Week 10	18/12/2014	897	31.3%	897	31.3%	897	31.3%
Week 11	25/12/2014	813	27.5%	810	27.4%	846	29.0%

From the differences shown in Table 3-7 it can be seen that delayed planting has a big impact in the achievable yield and hence the proceeds from sale of the produce. As with cotton, wheat crop planted earlier in the season would fetch better market prices than that planted later in the season as reported by IndexMundi (2016b). Crop planted in Week 5 and 7 would fetch US$2.6/ton higher than the crop planted in Weeks 9, 10 and 11. Considering the HBC command area (200,000ha), the regional loss in both achievable yield and revenue as a result of planting in any other week besides Week 5 is shown in Table 3-8. For example, shifting the planting date from Week 10 or 11 to Week 5 under all scheduling scenarios would bring an extra revenue of about US$ 400,000 while choosing Week 1 instead of Week 7 would bring about in an extra US$ 197,000.

Table 3-8 Yield and revenue forgone for wheat as a result of planting late in the season for the entire HBC

Scheduling Scenario	Yield forgone (tonnes)				Revenue forgone (US $)			
	Planting in Week				Planting in Week			
	7	9	10	11	7	9	10	11
PID	75.8	137.8	179.4	162.6	197,080	358,280	466,440	422,760
Scenario A	75.8	137.8	179.4	162.1	197,080	358,280	466,440	421,304
Scenario I	75.8	137.8	179.4	169.2	197,080	358,280	466,440	439,920

3.2.2. Effects of different planting dates and scheduling scenarios on conjunctive water use

The main source of water for crops in HBC command area is canal water while the secondary sources are rainfall and groundwater. Groundwater is obtained from two sources: water pumped directly from tubewells and then applied to the crops and water utilised by the crops as a result of capillary rise. The groundwater that constitutes capillary rise is assumed to come from water lost from the earthen canals into the shallow groundwater table and the water that percolates after rainfall or excess rainfall events.

Simulation results of water utilised from different sources by cotton and wheat as dictated by different planting dates and scheduling scenarios are presented here. The results have been obtained by aggregating and averaging the achievable yield from all the 17 distributaries serving the HBC command area. Total water used has been calculated by summing up contribution from surface flows (canals), rainfall, groundwater (tubewells) and capillary rise as shown in Equation (3.1).

$$TWU = SF + P + GW + CR \tag{3.1}$$

Where TWU is Total water used (mm), SF is surface flows (mm), P is rainfall (mm), GW is water from tubewells (mm) and CR is capillary rise (mm).

a. Water utilisation by cotton

Table 3-9 to Table 3-11 shows the simulated results of water utilised by cotton in Kharif 2014 for different planting dates across the three scheduling scenarios. Crop planted in the first week of Kharif 2014 consumes the highest amount of water while that planted in Week 10 uses the least amount of water for PID schedules. For both Scenario A and I, crop planted in week five utilises the highest amount of water while that planted in Week 10 uses the least. It can be observed that crop planted in Week 3 uses less water that the crop planted in both Week 5 and 8 for PID schedules, Week 1 for Scenario A schedules and Week 1 and 8 for Scenario I schedules.

Table 3-9 Simulated cotton water use based on PID scheduling

			PID-Kharif 2014 (Cotton)			
Week Number	**Planting date**	**Rainfall (mm)**	**GW Irrigation (mm)**	**Surface Irrigation (mm)**	**CR (mm)**	**Total water used (mm)**
Week 1	17/04/2014	231.0	179.94	308.12	255.73	974.79
Week 3	01/05/2014	232.8	149.06	303.18	261.09	946.13
Week 5	15/05/2014	233.0	165.65	293.82	279.65	972.12
Week 8	05/06/2014	233.0	148.06	269.18	300.65	950.88
Week 10	19/06/2014	205.2	120.59	254.35	295.08	875.22

Table 3-10 Simulated cotton water use based on Scenario A scheduling

			Scenario A-Kharif 2014 (Cotton)			
Week Number	**Planting date**	**Rainfall (mm)**	**GW Irrigation (mm)**	**Surface Irrigation (mm)**	**CR (mm)**	**Total water used(mm)**
Week 1	17/04/2014	231.0	198.06	228.76	256.38	913.40
Week 3	01/05/2014	232.8	201.24	220.41	254.80	909.25
Week 5	15/05/2014	233.0	210.88	208.88	274.65	927.41
Week 8	05/06/2014	233.0	164.47	192.53	306.12	896.12
Week 10	19/06/2014	205.2	150.76	179.82	289.96	825.75

Table 3-11 Simulated cotton water use based on Scenario I scheduling

		Scenario I-Kharif 2014 (Cotton)				
Week Number	Planting date	Rainfall (mm)	GW Irrigation (mm)	Surface Irrigation (mm)	CR (mm)	Total water used(mm)
Week 1	17/04/2014	231.0	178.71	293.65	255.08	957.64
Week 3	01/05/2014	232.8	171.53	287.06	244.27	935.66
Week 5	15/05/2014	233.0	176.41	272.41	277.65	959.47
Week 8	05/06/2014	233.0	175.88	247.12	292.29	948.29
Week 10	19/06/2014	205.2	149.59	231.59	288.38	874.75

Table 3-12 shows the percent contribution for each water source. Surface flows (primary source of water), accounts for 28-32%, rainfall accounts for 23-26%, groundwater (tubewells) accounts for 16-22 % while capillary rise contributes between 26-35%. No one single source of water is capable of providing the total amount of water required by the crop.

Table 3-12 Percent contribution of different water sources for cotton (Kharif 2014)

		Water Source			
Planting date	Scheduling Method	Rainfall	Groundwater	Surface flows	Capillary rise
17/04/2014 (Week 1)	PID	24%	18%	32%	26%
	Scenario A	25%	22%	25%	28%
	Scenario I	24%	19%	31%	27%
1/05/2014 (Week 3)	PID	25%	16%	32%	28%
	Scenario A	26%	22%	24%	28%
	Scenario I	25%	18%	31%	26%
15/05/2014 (Week 5)	PID	24%	17%	30%	29%
	Scenario A	25%	23%	23%	30%
	Scenario I	24%	18%	28%	29%
5/06/2014 (Week 8)	PID	25%	16%	28%	32%
	Scenario A	26%	18%	21%	34%
	Scenario I	25%	19%	26%	31%
16/06/2014 (Week 10)	PID	23%	14%	29%	34%
	Scenario A	25%	18%	22%	35%
	Scenario I	23%	17%	26%	33%

Comparison of the total water used on individual days between the PID scenario and both Scenario A and I indicate that PID scenario uses more water as shown in Table 3-13. PID scenario used between 37 and 60 mm (3.9-6.2%) more than Scenario A and between 0.5 and 16 mm (0.1-1.7%) more than Scenario I. The difference in the amount of water used by crop planted in Week 1 and subsequent weeks is shown in Table 3-14. There is a minimal difference (0.2-2.9%) between Week 1 and both Week 3 and 8 while there is some difference (8.7-10.1%) between Week 1 and 10. Crop planted in Week 5 under both Scenario A and I uses more water than that planted in Week 1 hence the positive sign in water consumption.

Table 3-13 Difference in the total amount of water used between PID schedules and Scenario A and I schedules based on the same planting date (cotton-Kharif 2014)

		Difference in amount of water used by other scenarios compared to PID			
		Scenario A		**Scenario I**	
Week Number	Planting date	mm	%	mm	%
Week 1	17/04/2014	60.6	6.2	16.4	1.7
Week 3	01/05/2014	36.9	3.9	10.5	1.1
Week 5	15/05/2014	44.7	4.6	12.6	1.3
Week 8	5/06/2014	54.8	5.8	2.6	0.3
Week 10	19/06/2014	49.5	5.7	0.5	0.1

Table 3-14 Difference in the total amount of water used for different planting dates and scheduling scenarios compared to Week 1 (cotton-Kharif 2014)

Difference in total amount of water used compared to Week 1							
		PID		**Scenario A**		**Scenario I**	
Week Number	Planting date	mm	%	mm	%	mm	%
Week 3	01/05/2014	-27.9	-2.9	-4.2	-0.5	-22.0	-2.3
Week 5	15/05/2014	-1.9	-0.2	14.0	1.5	1.8	0.2
Week 8	5/06/2014	-23.1	-2.4	-17.3	-1.9	-9.3	-1.0
Week 10	19/06/2014	-98.8	-10.1	-87.6	-9.6	-82.9	-8.7

Water from the different sources can be supplied at the same time or on different times as dictated by the plant water requirements and soil conditions. Figure 3-1 shows how these different sources of water supplies the crop as dictated by root zone depletion and transpiration for Hakra 5R distributary (Scenario A scheduling–Kharif 2014). It can be seen that there are days where water is supplied from a sole source while on other days, multiple sources. For example, on one day after planting (DAP), only water from surface sources is used but on Day 141, there is contribution from surface sources, rain and capillary rise. Th1 represents a threshold below which crop's canopy ceases to expand. If the water used (represented by depletion), is below TH1, the model triggers need to irrigate with groundwater to return the field to field capacity since surface flows are supplied weekly and rainfall and capillary rise cannot be controlled.

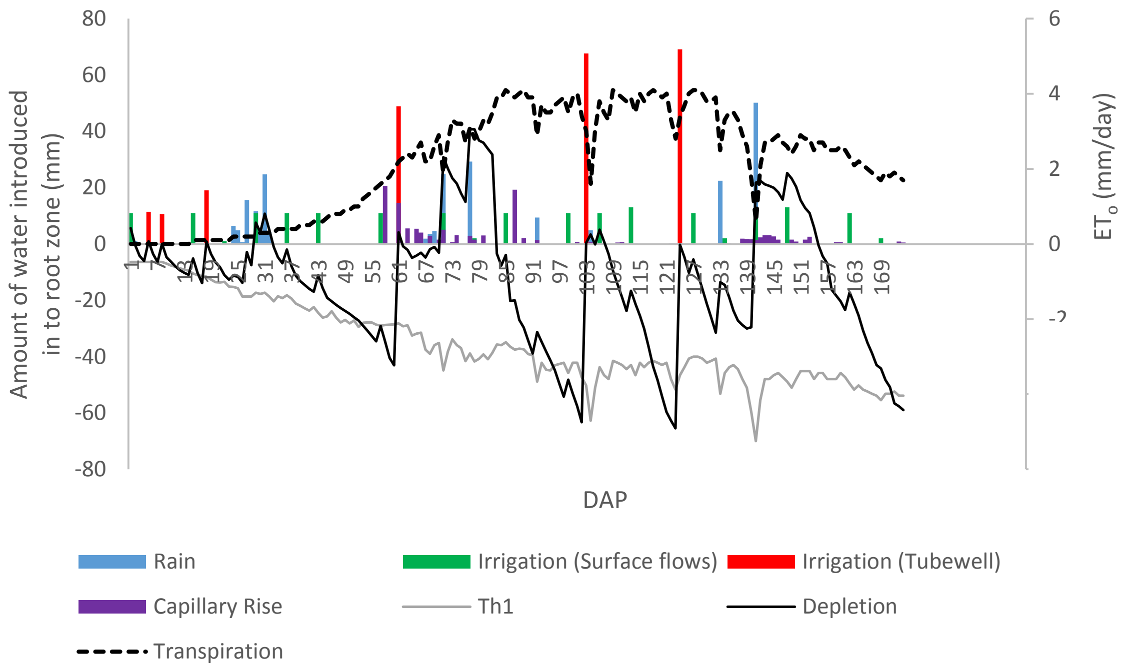


Figure 3-1 **Water supplied to the plant from various sources versus depletion for cotton crop (Kharif 2015)**

Considering all the planting dates, Scenario A schedules requires the highest amount of water from groundwater (tubewell) except in Week 8 where Scenario I schedules require more while PID schedules requires the least. Scenario I schedules require more groundwater from tubewells than PID schedules across all the planting dates as shown in Figure 3-2. This is because scheduling according to Scenario A provides in the lowest amount of surface flows across all the planting days. The difference between the surface water supplied is attributed to the way water is distributed in the season as the same amount of water is scheduled for all the scheduling scenarios.

Since extra cost is involved in procuring groundwater from tubewells (pumping cost or buying from the other farmers), it is important that deviation from the existing situation remains small. Comparison between the amounts of groundwater used across different dates between PID schedules and both Scenario A and I schedules for each day is as shown in Table 3-15. There is some difference in the amount of groundwater from tubewells required between the PID scenario and both Scenario A and I which lies between 10 and 35% for Scenario A and 5-19% for Scenario I

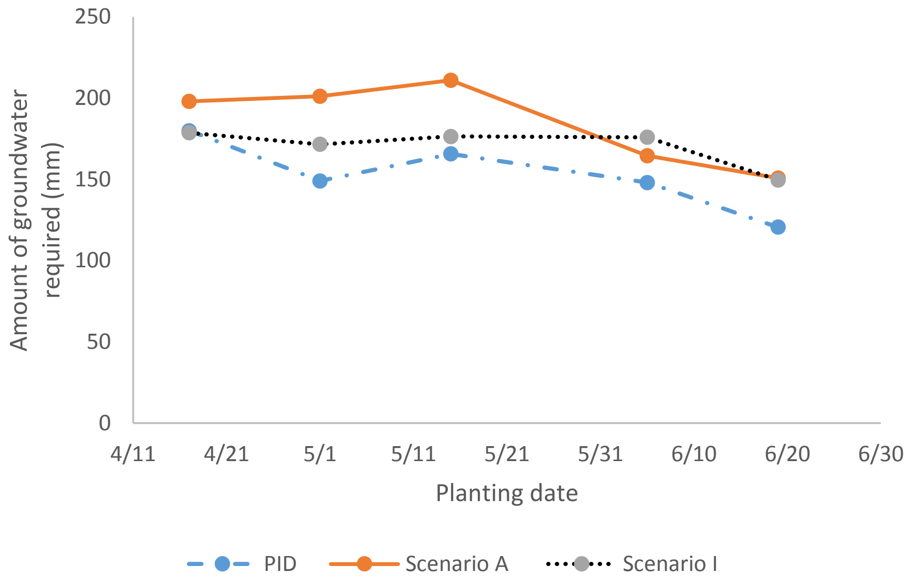


Figure 3-2 **Groundwater usage across different planting dates and scheduling scenarios**

Table 3-15 **Comparison of groundwater requirement between PID schedules and the other methods based on different planting dates**

		Scenario A		Scenario I	
Week Number	Planting date	mm	%	mm	%
Week 1	17/04/2014	18.1	10.1	(1.2)	(0.6)
Week 3	1/05/2014	52.2	35.0	22.5	11.2
Week 5	15/05/2014	45.2	27.3	10.8	5.1
Week 8	5/06/2014	16.4	11.1	27.8	16.9
Week 10	19/06/2014	30.2	25.0	29.0	19.2

The difference in the amount of tubewell water required by crop planted in Week 1 and subsequent weeks is shown in Table 3-16. There is a some difference between Week 1 and the subsequent weeks in the amount of tubewell water required for PID and Scenario A while the difference is minimal between PID and Scenario I. Crop planted in Week 3 and 5 under both Scenario A and I require more water than that planted in Week 1 hence the positive sign in water consumption.

Table 3-16 **Difference in the amount of groundwater (tubewell) of water used for different planting dates and scheduling scenarios compared to earliest planting date (cotton-Kharif 2014)**

		PID		Scenario A		Scenario I	
Week Number	Planting date	mm	%	mm	%	mm	%
Week 3	5/1/2014	-30.9	-3.2	3.2	0.3	-7.2	-0.7
Week 5	5/15/2014	-14.3	-1.5	12.8	1.4	-2.3	-0.2
Week 8	6/5/2014	-31.9	-3.3	-33.6	-3.7	-2.8	-0.3
Week 10	6/19/2014	-59.4	-6.1	-47.3	-5.2	-29.1	-3.0

Simulation results for on 16/4/2015 (Week 1 of Kharif 2015) as the planting date are as shown in Table 3-17 . Rainfall and capillary rise are the major contributors of water during this growing period although surface flows are supposed to be the main source of water. Rainfall contributes about 37%, capillary rise contributes about 47%, groundwater (tubewells) contributes 10% while surface flows contributes about 6% of the total amount utilised by the crop. There is an increase in the amount of rainfall in Kharif 2015 which led to rise in the shallow groundwater table (Figure 2-5). Capillary rise is the major contributor for crop water for all three scheduling scenarios.

Table 3-17 Simulated cotton water use for Kharif 2015 based on all scheduling scenarios

Scheduling Scenario	Rainfall		GW Irrigation (mm)		Surface Irrigation (mm)		CR (mm)		Total water used (mm)
	mm	%	mm	%	mm	%	mm	%	
PID	321.8	37	83.61	10	51.83	6	402.94	47	860.19
Scenario A	321.8	37	89.89	10	45.17	5	400.17	47	857.02
Scenario I	321.8	37	90.71	11	51.00	6	401.35	47	864.86

In comparison to Kharif 2014, the water used in Kharif 2015 is less by 11% for PID, 6% for Scenario A and 10% for Scenario I but individually, both rainfall and capillary rise contribute higher amounts in Kharif 2015 than in Kharif 2014.

b. Water utilisation by wheat

Table 3-18 to Table 3-20 shows the simulated results of water used in Rabi 2014/2015 by wheat for different planting dates across the three scheduling scenarios. Wheat crop planted in the Week 11 of Rabi 2014/2015 uses the highest amount of water for the three scheduling scenarios. Week 7 crop uses the least water for PID schedules while Week 5 crop uses the least for both Scenario A and I. It can also be seen that Week 10 crop uses less water than Week 9 crop hence water usage does not increase linearly as the season progresses.

Table 3-18 Simulated wheat water use based on PID scheduling

PID-Rabi 2014/2015 (Wheat)						
Week Number	Planting date	Rainfall (mm)	GW Irrigation (mm)	Surface Irrigation (mm)	CR (mm)	Total water used (mm)
Week 5	13/11/2014	102.6	0.0	60.76	171.31	334.67
Week 7	27/11/2014	102.4	0.0	55.59	173.40	331.39
Week 9	11/12/2014	102	0.0	54.18	181.82	338.00
Week 10	18/12/2014	101.2	0.0	53.12	180.91	335.22
Week 11	25/12/2014	102.9	0.0	53.35	184.69	340.95

Table 3-19 Simulated wheat water use based on Scenario A scheduling

			Scenario A- Rabi 2014/2015 (Wheat)			
Week Number	**Planting date**	**Rainfall (mm)**	**GW Irrigation (mm)**	**Surface Irrigation (mm)**	**CR (mm)**	**Total water used(mm)**
Week 5	13/11/2014	102.6	0.0	47.06	173.54	323.20
Week 7	27/11/2014	102.4	0.0	46.18	175.87	324.45
Week 9	11/12/2014	102.0	0.0	46.41	184.71	333.12
Week 10	18/12/2014	101.2	0.0	46.35	182.96	330.52
Week 11	25/12/2014	102.9	0.0	47.18	190.28	340.36

Table 3-20 Simulated wheat water use based on Scenario I scheduling

			Scenario I- Rabi 2014/2015 (Wheat)			
Week Number	**Planting date**	**Rainfall (mm)**	**GW Irrigation (mm)**	**Surface Irrigation (mm)**	**CR (mm)**	**Total water used(mm)**
Week 5	13/11/2014	102.6	0.0	51.59	170.78	324.96
Week 7	27/11/2014	102.4	0.0	50.35	174.05	326.80
Week 9	11/12/2014	102	0.0	50.41	181.71	334.12
Week 10	18/12/2014	101.2	0.0	50.18	181.44	332.81
Week 11	25/12/2014	102.9	0.0	51.00	188.75	342.65

Table 3-21 shows the percent contribution for each water source. Surface flows (primary source of water), accounts for 14-16%, rainfall accounts 30-32% while capillary rise accounts for between 51 and 56% (biggest contributor to wheat crop water requirements). There is no need to supply more water from the tubewell for the three scheduling scenarios as water from surface flows, rainfall and capillary rise meets the crop's water requirements.

Table 3-21 Percent contribution of different water sources (Wheat- Rabi 2014/2015)

Planting date	**Scheduling Method**	**Rainfall**	**Groundwater**	**Surface flows**	**Capillary rise**
13/11/2014 (Week 5)	PID	31%	0%	18%	51%
	Scenario A	32%	0%	15%	54%
	Scenario I	32%	0%	16%	53%
27/11/2014 (Week 7	PID	31%	0%	17%	52%
	Scenario A	32%	0%	14%	54%
	Scenario I	31%	0%	15%	53%
11/12/2014 (Week 9)	PID	30%	0%	16%	54%
	Scenario A	31%	0%	14%	55%
	Scenario I	31%	0%	15%	54%

Planting date	Scheduling Method	Rainfall	Groundwater	Surface flows	Capillary rise
18/12/2014 (Week 10)	PID	30%	0%	16%	54%
	Scenario A	31%	0%	14%	55%
	Scenario I	30%	0%	15%	55%
25/12/2014 (Week 11)	PID	30%	0%	16%	54%
	Scenario A	30%	0%	14%	56%
	Scenario I	30%	0%	15%	55%

Comparison of the total water used on individual days between the PID scenario and both Scenario A and Scenario I indicates that current scenario used more water, as shown in Table 3-22. PID scenario uses between 0.6 and 11.5 mm (0.2-3.4%) more than Scenario A and between 0.7 and 2.9 mm (0.7-2.9%) more than Scenario I. The difference in the amount of water used by crop planted in Week 5 and subsequent weeks is shown in

Table 3-23. There is minimal difference in the amount of water used between the weeks as it varies between 0.2 and 1.9% for PID, 0.4 and 5.3% for Scenario A and 0.6 and 5.4% for Scenario A schedules.

Table 3-22 Difference in the total amount of water used between PID schedules and Scenario A and I schedules based on the same planting date (Wheat-Rabi 2014/2015)

		Difference			
		Scenario A		Scenario I	
Week Number	Planting date	mm	%	mm	%
Week 5	13/11/2014	11.5	3.4	10	2.9
Week 7	27/11/2014	6.9	2.1	4.6	1.4
Week 9	11/12/2014	4.9	1.4	3.9	1.1
Week 10	18/12/2014	4.7	1.4	2.4	0.7
Week 11	25/12/2014	0.6	0.2	-1.7	-0.5

Table 3-23 Difference in the total amount of water saved for different planting dates and scheduling scenarios compared to earliest planting date(Wheat-Rabi 2014/2015)

		Difference					
		PID		Scenario A		Scenario I	
Week Number	Planting date	mm	%	mm	%	mm	%
Week 7	11/27/2014	-3.3	-1.0	1.2	0.4	1.8	0.6
Week 9	12/11/2014	3.3	1.0	9.9	3.1	9.2	2.8
Week 10	12/18/2014	0.6	0.2	7.3	2.3	7.8	2.4
Week 11	12/25/2014	6.3	1.9	17.2	5.3	17.7	5.4

Figure 3-3 shows how the different sources of water supplied water to the crop as dictated by root zone depletion and transpiration for Hakra 5R distributary (Scenario A scheduling–Rabi 2014/2015). It can be seen that there are days that different sources supply water independently while on other days, they are combined to meet the water requirement. For example, early surface flows and capillary rise were available while later (day 71), there is combination of capillary rise and rainfall. Th1 represents a threshold below which crop's canopy ceases to expand. If the water used (represented by depletion), is below TH1, the model triggers need to irrigate with groundwater to return the field to field capacity since surface flows are supplied weekly and rainfall and capillary rise cannot be controlled. There was no instant at which this happened and hence no groundwater from tubewells was supplied.

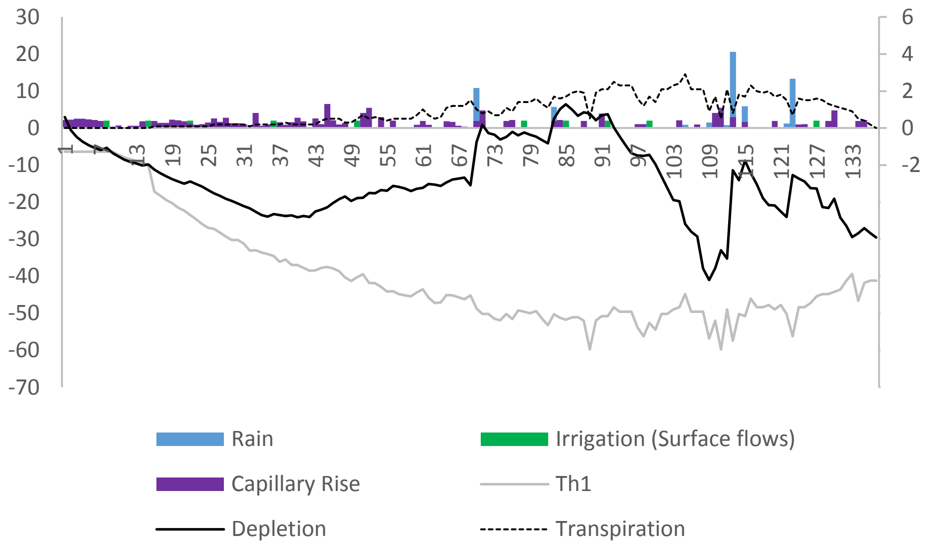


Figure 3-3 Water supplied to the wheat crop from various sources

3.2.3. Effects of different planting dates and scheduling scenarios on root zone depletion

Root zone depletion (Dr), the amount of water required to bring the root zone back to field capacity, is calculated as the difference between soil water content at field capacity and soil water content of the root zone as shown in equation (3.2)

$$Dr = Wr_{FC} - Wr \tag{3.2}$$

Where *Dr* is root zone depletion (mm), Wr_{FC} is soil water content of the root zone at field capacity (mm) and *Wr* is the soil water content of the root zone expressed as depth (mm).

Root zone depletion can either be positive or negative depending on the natural phenomenon occurring (rain falling or lack of rain) and/or management decisions made (irrigation). Heavy rainfall or a large amount of irrigation event can lead to the root zone being temporarily above the field capacity (waterlogging or saturation or flooding). Depletion of the root zone for the HBC command area at the end of growing season is determined by aggregating and averaging depletion from all the 17 distributaries as dictated by planting date and scheduling method.

a. Depletion due to cotton crop

Table 3-24 and Figure 3-4 shows the root zone depletion as a result of planting cotton crop on different dates and using different scenarios. The general trend for all the three scheduling scenarios is that the crop planted in Week 1 of Kharif 2014 caused the highest depletion while the least depletion was caused by the crop planted in Week 5. Depletion due to PID schedules ranges between 21 and 37 mm, 27 and 47mm due to Scenario A schedules and 14 and 36 mm due to Scenario I schedules. Comparing the scenarios on the same planting date shows that Scenario I causes the least depletion on any given planting date while Scenario A causes the most except on Week 3 where PID schedule had the most depletion.

Table 3-24 Root zone depletion for different planting dates and scheduling scenarios for Kharif 2014

Week Number	Planting date	PID	Depletion Scenario A	Scenario I
Week 1	17/04/2014	36.9	47.4	36.3
Week 3	01/05/2014	34.4	26.5	20.5
Week 5	15/05/2014	20.9	26.8	14.4
Week 8	05/06/2014	26.7	37.9	24.7
Week 10	19/06/2014	25.2	36.4	25.0

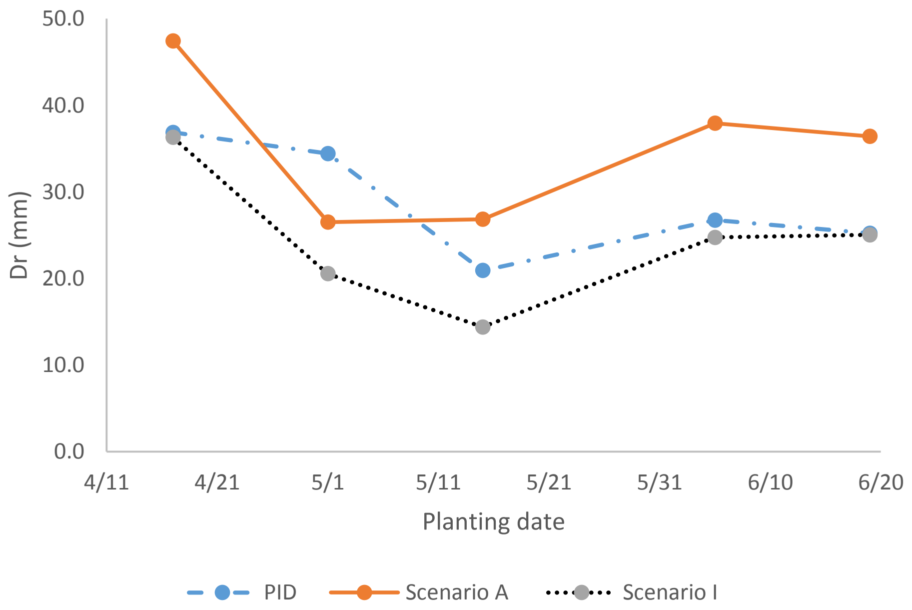


Figure 3-4 Root zone depletion for different planting dates and scheduling scenarios (cotton)

For Week 1 of Kharif 2015 (based on 16/04/2015 as the planting date), the corresponding root zone depletion is as shown in Table 3-25. It can be see that all the schedules have a negative value of depletion. This means that the soil water content at the end of the cropping period had more water that the field capacity. PID schedules had the higher amount of water in the root zone while Scenario A still had the lower value between the three scenarios.

Table 3-25 Root zone depletion for different planting dates and scheduling scenarios for Kharif 2015

Scheduling Scenario	Depletion (mm)
PID	-12.7
Scenario A	-11.4
Scenario I	-12.1

Comparing Week 1 of Kharif 2014 with Week 1 of Kharif 2015 shows Scenario A still causes the most depletion in the root zone. There is minimal difference in root zone depletion that is caused by both PID and Scenario I with Scenario I causing slightly higher depletion in 2014 while PID causes slightly higher depletion in 2014.

b. Depletion due to wheat crop

Table 3-26 and Figure 3-5 shows the root zone depletion as a result of planting wheat crop on different dates and using different scenarios. The general trend for all the three scheduling scenarios is that the crop planted in Week 10 of Rabi 2014/2015 causes the highest depletion while the least depletion is caused by the crop planted in Week 7. Depletion due to PID schedules ranges between 13 and 41 mm, 19 and 43mm due to Scenario A schedules and 18 and 42 mm due to Scenario I schedules. Comparing the scenarios on the same planting date shows that PID schedules causes the least depletion on any given planting date while Scenario A causes the most. More depletion occurs as the planting date progresses into the season due to increase in temperature.

Table 3-26 Root zone depletion for different planting dates and scheduling scenarios for Rabi 2014/2015

		Depletion		
Week Number	Planting date	PID	Scenario A	Scenario I
Week 5	13/11/2014	19.7	23.9	21.8
Week 7	27/11/2014	13.2	19.3	18.4
Week 9	11/12/2014	30.5	33.0	32.7
Week 10	18/12/2014	40.5	43.1	42.3
Week 11	25/12/2014	37.5	39.5	38.0

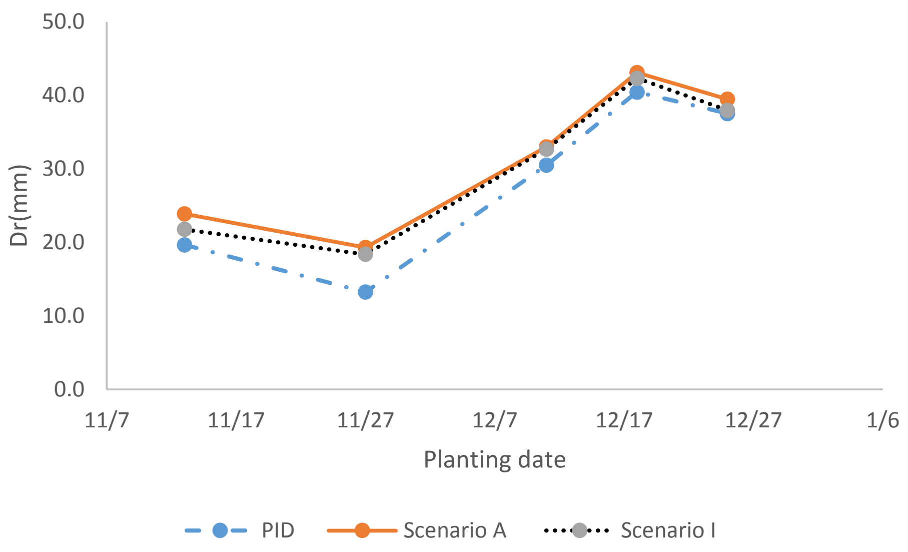


Figure 3-5 Root zone depletion for different planting dates and scheduling scenarios (wheat)

3.2.4. Effects of different planting dates and scheduling scenarios on salt accumulation

The HBC command area's soils have some degree of salt accumulation in the soil profile due to the upward movement of natural salts from alluvial deposits into the root zone as a result of rapid rise in water table as explained in section 1.4.4. Apart from the natural occurrence of salts in the soil profile, irrigation water used to supplement the surface flows contains some salts. Specific conductivity of water used in the HBC command area is shown in Table 3-27.

Table 3-27 Specific conductivity of water used in the HBC command area

Water source	Specific conductivity (dS/m)
Surface flows	0.2
Deep tubewells	0.3-4.6 (Average of 2.5)
Shallow groundwater table (capillary rise)	1-25
Rainfall	N/A(assumed to contain no dissolved salts)

Since all these sources of water are combined to meet the water requirements of the crop, they might have an influence in salt build up on the soil profile under different crops depending on the amount of water applied to the field. Salts are leached out of the soil profile by drainage water and if this water is not enough, salt accumulation will occur. The net effect of different scheduling scenarios and planting dates is calculated as shown in Equation (3.3) while the total amount of salts in the profile is calculated as shown in Equation (3.4).

$$NSA = SD - (SI + SU) \tag{3.3}$$

$$TSL = ISL + NA \tag{3.4}$$

Where *NA* is net salt accumulation (ton/ha), *SD* is amount of salt drained (ton/ha), *SI* is the amount of salt brought into the soil profile from irrigation (ton/ha), *TSL* is the total amount of salt at the end of a growing season (ton/ha) and *ISL* is the total amount of salts at the beginning of the growing season (ton/ha).

a. Salt balance as a result of cotton cultivation

The simulated salt accumulation as a result of planting cotton on different dates of Kharif 2014 and using different scheduling scenarios is shown in Table 3-28 to Table 3-30. The amount of salt in the soil profile is calculated as indicated in Equation (3.4).

$$Salt_{cell} = 0.64W_{cell} \times EC_{cell} \tag{3.5}$$

$$W_{cell} = 1000\left(\frac{\theta_{sat}}{n}\right) \times \Delta z \tag{3.6}$$

Where $Salt_{cell}$ is salt content (g/m^2), W_{cell} is the volume of cell in mm (water), EC_{cell} is the specific conductivity of the saturated soil paste in the cell, Θ_{sat} is the soil water content at saturation (m^3/m^3) of the soil horizon, *n* is the number of cells and *Δz* is the thickness of soil compartment (m). 0.64 is a global conversion factor used by the model to convert dS/m in gram salts per litre (1dS/m = 0.64 g/l).

For this reach, the EC_{cell} has been interpolated from the values of initial EC_e of the soil profile presented in Table 2-8 while the soil water content at saturation is the model's default value. The effective root depth (function of type of crop planted) is broken down into 12 compartments of equal thickness while each compartment is broken into 12 cells. The total amount of salt is calculated by adding up the salt content of each cell in the effective rooting depth and has been determined as 11.50 ton/ha for an effective rooting depth of 1.8m for cotton.

The net accumulation of salts for the three scheduling scenarios on different planting dates is negative. This means that the water supplied is enough to drain all the salts that came in to the soil profile from surface and tubewell sources (salt in) and capillary rise (salt up). PID schedules are able to drain the most salts except in Week 3 when Scenario I schedules drains the most salts while Scenario A drains the least.

Table 3-28 Salt balance for Kharif 2014 using PID schedules

PID-Kharif 2014 (Cotton)							
Week number	Planting date	Salt at start of season (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net drained (ton/ha)	Salt at end of season (ton/ha)
Week 1	17/04/2014	11.50	2.73	12.19	6.01	-3.44	8.06
Week 3	01/05/2014		2.27	11.72	6.25	-3.20	8.30
Week 5	15/05/2014		2.51	12.84	7.22	-3.10	8.39
Week 8	05/06/2014		2.16	14.24	8.55	-3.53	7.97
Week 10	19/06/2014		1.73	14.15	9.06	-3.36	8.14

Table 3-29 Salt balance for Kharif 2014 using Scenario A schedules

Scenario A Kharif 2014 (Cotton)							
Week number	Planting date	Salt at start of season (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net drained (ton/ha)	Salt at end of season (ton/ha)
Week 1	17/04/2014	11.50	2.95	11.47	6.22	-2.29	9.20
Week 3	1/05/2014		2.88	11.39	6.37	-2.14	9.36
Week 5	15/05/2014		3.13	13.18	7.22	-2.83	8.67
Week 8	5/06/2014		2.50	13.63	8.73	-2.39	9.10
Week 10	19/06/2014		2.21	13.96	9.05	-2.70	8.80

Table 3-30 Salt balance for Kharif 2014 using Scenario I schedules

Scenario I Kharif 2014 (Cotton)							
Week number	Planting date	Salt at start of season (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net drained (ton/ha)	Salt at end of season (ton/ha)
Week 1	17/04/2014	11.50	2.59	11.78	6.15	-3.04	8.45
Week 3	1/05/2014		2.43	12.47	6.02	-4.02	7.47
Week 5	15/05/2014		2.60	12.53	7.44	-2.49	9.01
Week 8	5/06/2014		2.67	14.39	8.21	-3.52	7.98
Week 10	19/06/2014		2.17	14.56	9.00	-3.39	8.11

Of the various sources of water, the capillary rise (salt up) brings the most amount of salts into the soil profile; 2-3 times the amount from surface flows and tubewell water (salt in) combined. It can be seen that salt moving up the soil profile increases significantly for crop planted in Week 5 to Week 10 for all the three scheduling scenarios. Also the amount of salts leached out is higher for the same three weeks as compared to crop planted in Week 1 and 3 for all the three scheduling scenarios. Net accumulation of salts in the profile as a result of cotton cultivation in Kharif 2014 is illustrated in Figure 3-6.

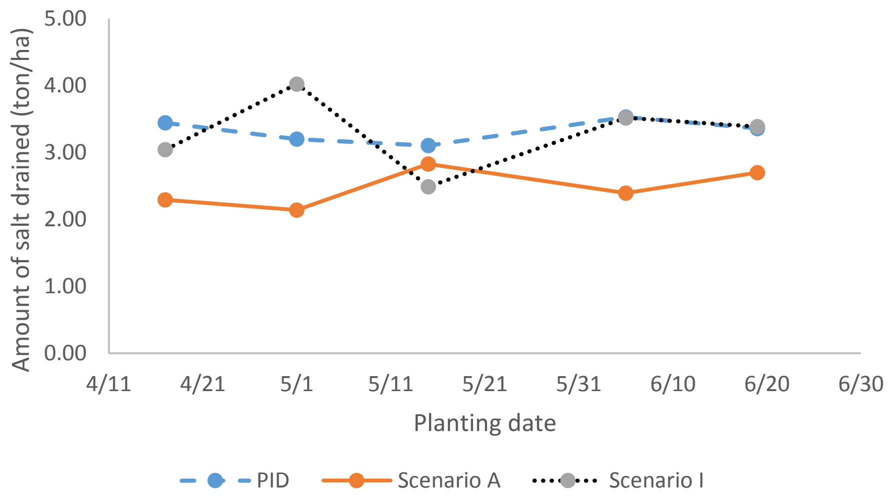


**Figure 3-6	Net salt reduction across different planting dates and scheduling scenarios**

The total amount of salt at the end of the season is highest as a result of using Scenario A schedules except in Week 5 when Scenario I leads to higher accumulation as shown in Figure 3-7. Total salt load in the profile correspond linearly to the net amount of salt drained as Scenario A drains the least but has the highest load in the profile.

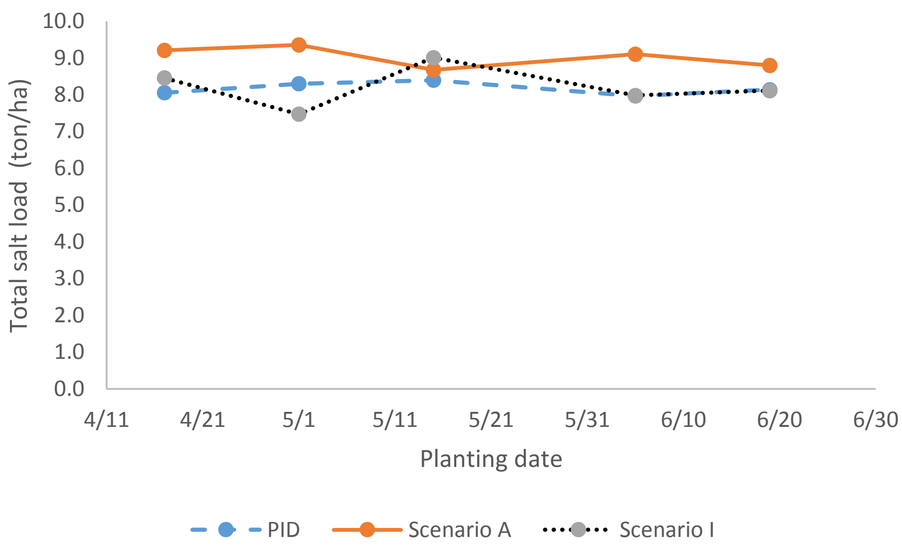


**Figure 3-7	Total salt load for cotton across the planting dates and scheduling scenarios**

The results of simulating the effect of different scheduling scenarios for cotton in Kharif 2015 indicate there is net addition of salt in the root zone as shown in Table 3-31. This is because the amount of salt entering the root zone is more than the amount of salt being leached by drainage water. Based on this one planting date, there is no difference between the amount of salt deposited by both PID and Scenario I schedules but Scenario A deposits about 80kg/ha less than both PID and Scenario I. Capillary rise, as in Kharif 20104, is the major source of salt deposited in the root zone, bring up almost 15 times more than surface flows. The amount of salt at the begging of Kharif 2015 is the same as that at the beginning of Kharif 2014 because the model is not able to reflect changes in salt load in the soil profile. There is a minimal difference in the net load of the salt at the end of the season since the influx and drainage of salt due to the three scheduling scenarios is similar.

Table 3-31 Salt balance for Kharif 2015 based on all scheduling scenarios

Kharif 2015 (cotton)						
Scheduling method	Salt at start of season -1.8m (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net effect (ton/ha)	Salt at end of season (ton/ha)
PID		1.34	13.69	20.18	7.82	19.32
Scenario A	11.50	1.44	13.73	20.03	7.74	19.24
Scenario I		1.45	13.73	20.10	7.82	19.32

The results presented in Table 3-28 to Table 3-31, give a snapshot at the beginning and end of the cropping seasons, Kharif 2014 and Kharif 2015 and present the amount of salts in the soil in terms of mass value. Knowledge on the specific conductivity of the soil paste is also important as it gives on an indication of how the concentration of salts influenced the crop's growth in terms of salinity stresses. The ECe of saturated soil extract is in the root zone is calculated per soil compartment and then summed up to determine the overall ECe of the soil profile using Equation (3.7).

$$EC_e = \left(\frac{\sum_{j=1}^{n} Salt_{Cell,j}}{0.64\ (1000\theta_{sat}\Delta z)} \right) \tag{3.7}$$

Where EC_e is the specific conductivity of the saturated soil paste at a particular soil depth, Θ_{sat} is the soil water content at saturation (m^3/m^3), n is the number of cells and Δz *(m)* is the thickness of soil compartment

Results of simulated specific conductivity of the saturated soil extract from the root zone due to different planting dates and scheduling scenarios for cotton crop are shown in Figure 3-8 to Figure 3-12 for Kharif 2014 and Figure 3-13 for Kharif 2015.

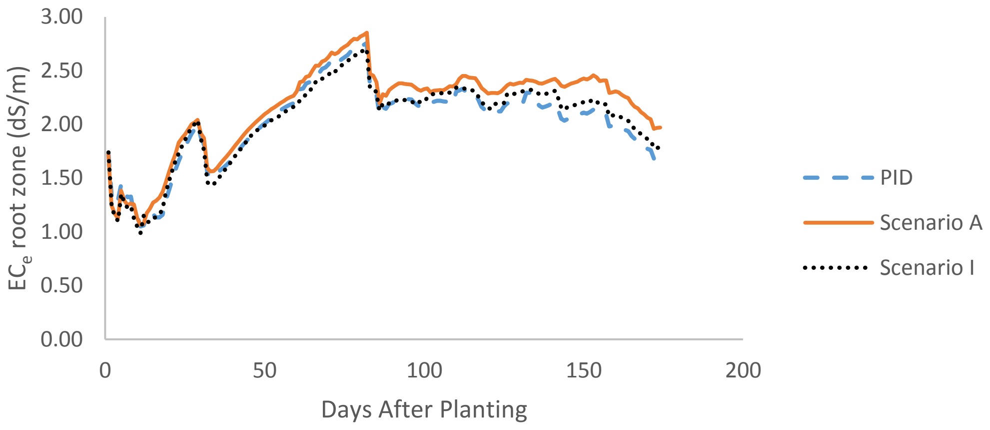


Figure 3-8 **Simulated soil salinity in the root zone of cotton for different scheduling scenarios – Kharif 2014 Week 1**

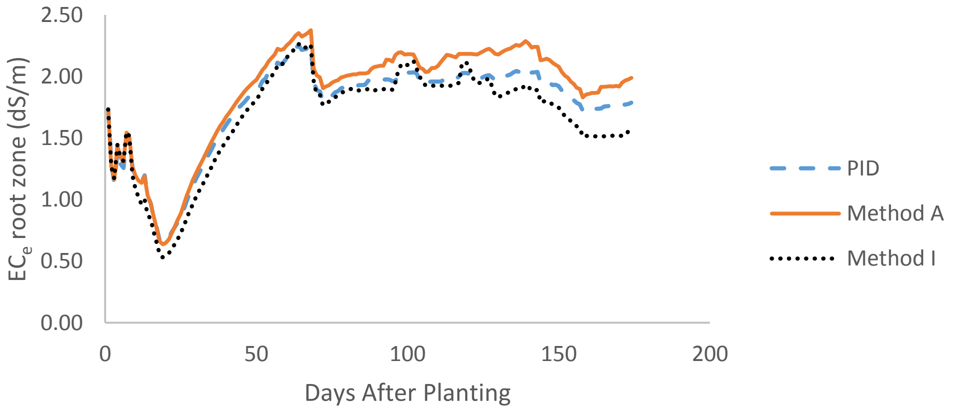


Figure 3-9 **Simulated soil salinity in the root zone of cotton for different scheduling scenarios – Kharif 2014 Week 3**

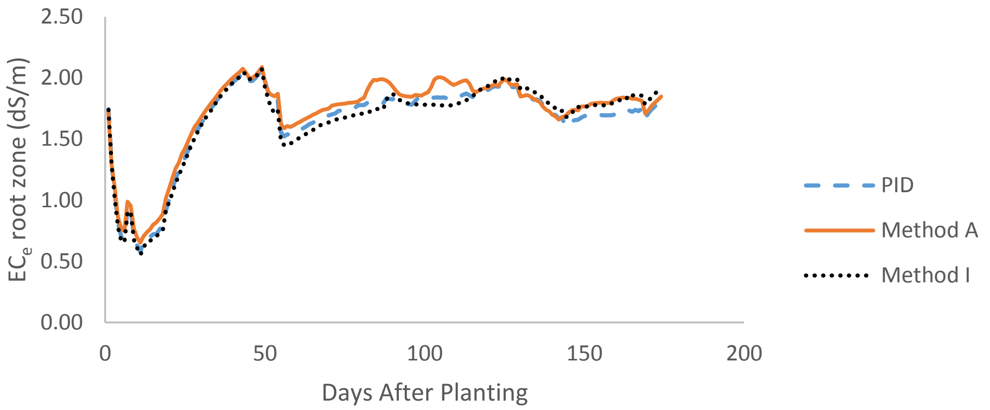


Figure 3-10 **Simulated soil salinity in the root zone of cotton for different scheduling scenarios – Kharif 2014 Week 5**

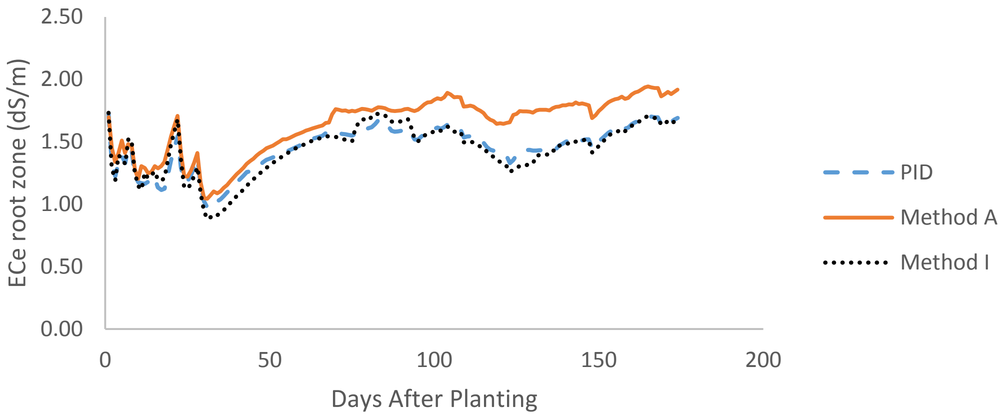


Figure 3-11 **Simulated soil salinity in the root zone of cotton for different scheduling scenarios – Kharif 2014 Week 8**

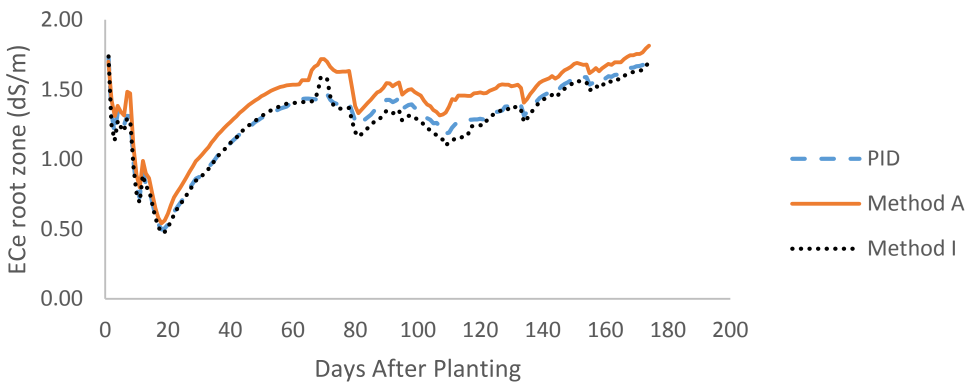


Figure 3-12 **Simulated soil salinity in the root zone of cotton for different scheduling scenarios – Kharif 2014 Week 10**

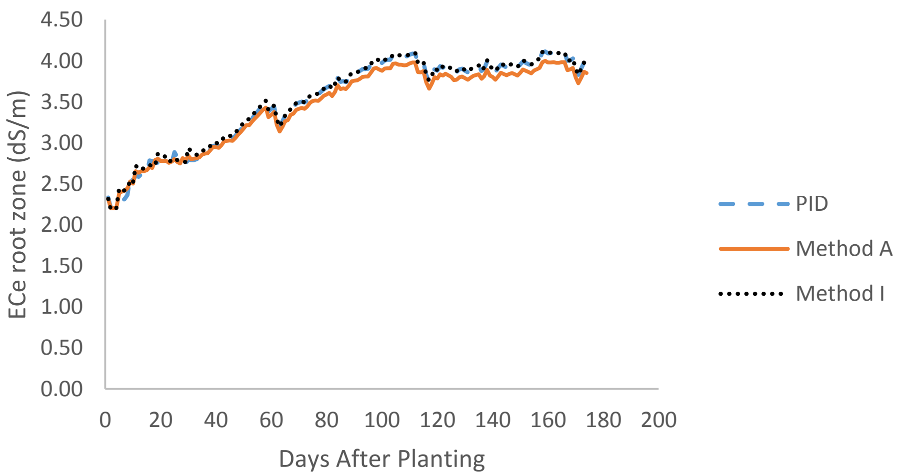


Figure 3-13 **Simulated soil salinity in the root zone of cotton for different scheduling scenarios – Kharif 2015 Week 1**

The results show that the EC_e of saturated soil extract as a result of irrigating with Scenario A schedules is higher throughout the growing season for all the planting dates selected except from day 117 of the crop planted in Week 5 of Kharif 2014 where Scenario I schedule has a higher value of EC_e. PID and Scenario A schedules produce a near identical EC_e profile throughout the growing period but Scenario I has a slightly lower EC_e except for Week 1 and Week 5.

EC_e recorded for Kharif 2015 for all scenarios shows a rising trend. Scheduling according to Scenario A shows a lower value of EC_e of the root zone but the difference from other methods is minimal. This is due to the high capillary rise of water from the shallow groundwater table for all the scheduling scenarios.

The effect of soil salinity on the crop yield (biomass) is determined by the EC_e of water in the effective rooting depth. In case of HBC command area, the average EC_e of saturated soil paste in the effective root zone was between 0.5 dS/m and 4.1 dS/m across all the scheduling scenarios as shown in the figures above. Cotton, being the crop under consideration cultivation, is not affected by even the highest value recorded as it starts to loose yield if the EC_e of saturated soil paste in the root zone is greater than 7.7dS/m.

b. Salt balance as a result of wheat cultivation

The salt balance as simulated from different planting dates and irrigation methods for wheat crop is as presented in Table 3-32 to Table 3-34. The amount of salt at the beginning of the season in the effective root zone of 1.55m has been simulated as 9.56 ton/ha using the same procedure as for cotton (model is not able to keep the salinity status at the end of the previous season, hence initial specific conductivity of the soil as shown in Table 2-8 is used).

Table 3-32 Salt balance for Rabi14-15 using PID schedules

PID Rabi14-15 (Wheat)							
Week Number	Planting date	Salt at start of season (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net accumulation (ton/ha)	Salt at end of season (ton/ha)
Week 5	13/11/2014	9.56	0.78	6.10	7.61	2.24	11.85
Week 7	27/11/2014		0.75	6.10	7.88	2.51	12.10
Week 9	11/12/2014		0.75	6.39	8.40	2.74	12.33
Week 10	18/12/2014		0.75	6.84	8.45	2.34	11.93
Week 11	25/12/2014		0.75	6.83	8.80	2.71	12.28

Table 3-33 Salt balance for Rabi14-15 using Scenario A schedules

Scenario A Rabi14-15 (Wheat)							
Week Number	Planting date	Salt at start of season (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net accumulation (ton/ha)	Salt at end of season (ton/ha)
Week 5	13/11/2014		0.68	6.02	7.67	2.33	11.90
Week 7	27/11/2014		0.68	5.99	7.95	2.63	12.20
Week 9	11/12/2014	9.56	0.68	6.26	8.51	2.94	12.50
Week 10	18/12/2014		0.68	6.78	8.44	2.34	11.90
Week 11	25/12/2014		0.68	6.73	8.84	2.79	12.35

Table 3-34 Salt balance for Rabi14-15 using Scenario I schedules

Scenario I Rabi14-15 (Wheat)							
Week Number	Planting date	Salt at start of season (ton/ha)	Salt In (ton/ha)	Salt Out (ton/ha)	Salt Up (ton/ha)	Net accumulation (ton/ha)	Salt at end of season (ton/ha)
Week 5	13/11/2014		0.73	6.01	7.65	2.37	11.93
Week 7	27/11/2014		0.73	6.00	7.90	2.63	12.20
Week 9	11/12/2014	9.56	0.73	6.29	8.38	2.83	12.39
Week 10	18/12/2014		0.73	6.79	8.38	2.33	11.89
Week 11	25/12/2014		0.73	6.73	8.80	2.81	12.37

From the simulated results, it can be observed that the net accumulation is positive which means that the amount of salts entering the root zone is more than the amount of salts leaving. Irrigating using PID schedules results in to marginally lower amounts of deposited salts while Scenario A contributes marginally higher deposits .There is minimal difference in the amount of salt accumulated due to the different schedules at different planting days as shown in Figure 3-14.

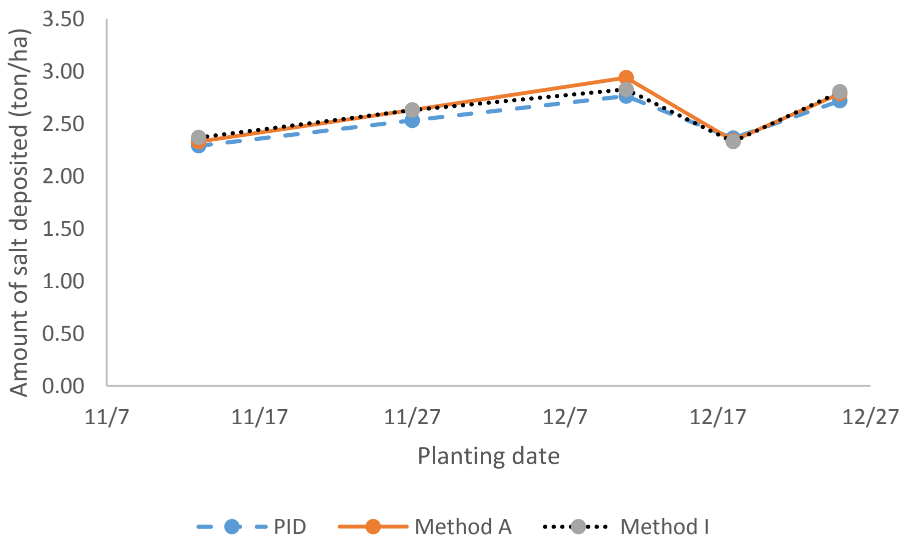


Figure 3-14 Net salt addition across different planting date and scheduling scenarios

The most salt deposition by the three scheduling scenarios occurs due the crop planted in Week 9 while the least is deposited as a result of planting in Week 3. There is a convergence of the amount of salt deposited by the three scheduling scenarios as a result of planting in Week 10. As with the cotton crop in Kharif 2014 and 2015, capillary rise is the major contributor of salts in the root zone. It accounts for about 15 times more than the amount brought in by surface flows since there was no irrigation from tubewell water.

As expected, the total load of salt at the end of the growing period is higher than at the beginning of the growing season for all the scheduling scenarios and planting dates. PID scenario leads to marginally lesser salt accumulation for all the planting days selected except in Week 10 where total load due to all scenarios is the same. The difference in Scenario A and I is minimal with Scenario I accumulation more salts in Week 5 while Scenario A accumulates more in Week 9 as shown in Figure 3-15.

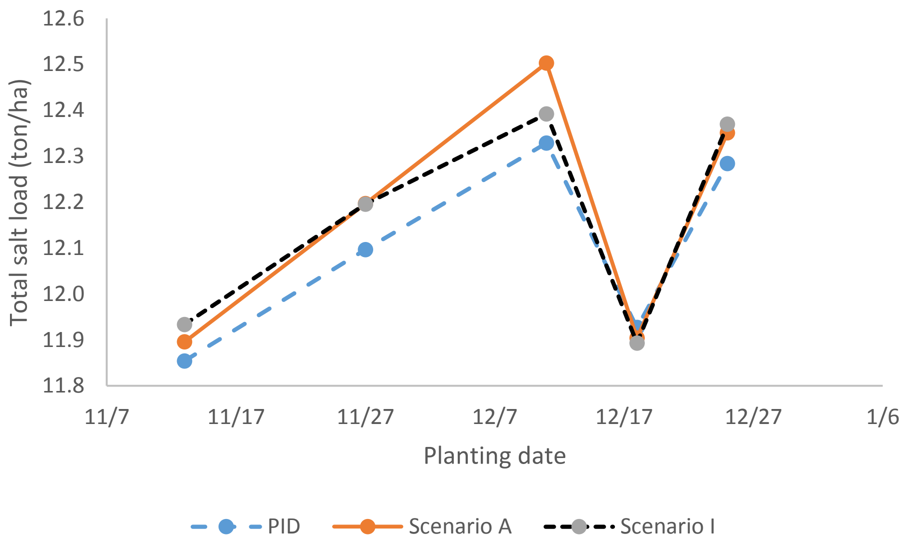


Figure 3-15 Total salt load for wheat across the planting dates and scheduling scenarios

Results of simulated specific conductivity of the saturated soil extract from the root zone due to different planting dates and scheduling scenarios for cotton crop are shown in shown in Figure 3-16 to Figure 3-20 (calculated using Equation (3.7)).. It can be seen that irrigating using any of the scheduling method results in higher values of EC_e in the root zone at the end of growing season as compared to when the crop was planted. Although PID schedules results into lower values of EC_e in the root zone, the difference with the other scheduling scenarios is minimal.

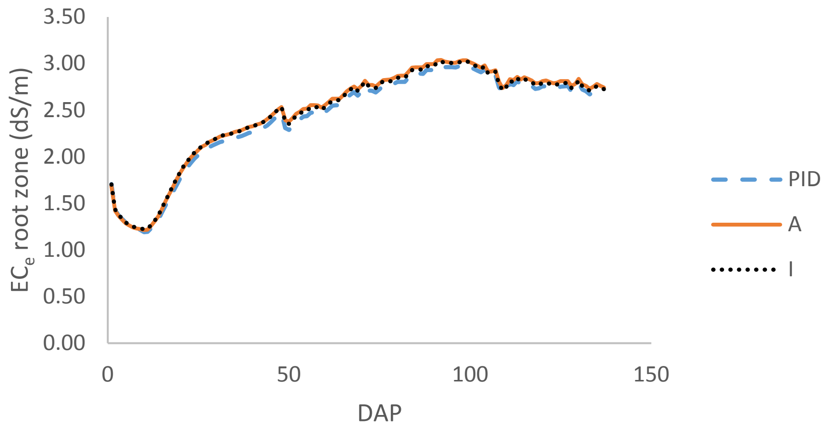


Figure 3-16 **Simulated soil salinity in the root zone of wheat for different scheduling scenarios – Kharif 2015 Week 5**

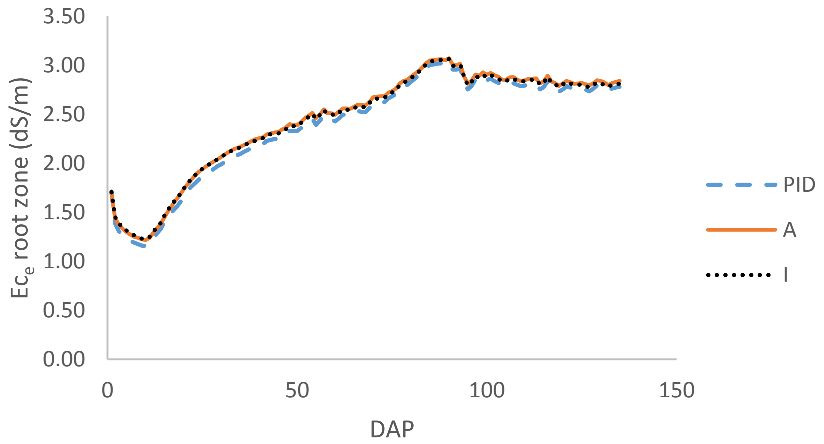


Figure 3-17 **Simulated soil salinity in the root zone of wheat for different scheduling scenarios – Kharif 2015 Week 7**

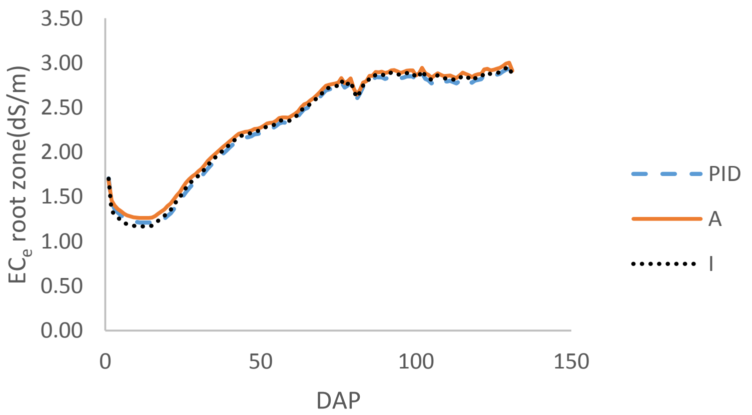


Figure 3-18 **Simulated soil salinity in the root zone of wheat for different scheduling scenarios – Kharif 2015 Week 9**

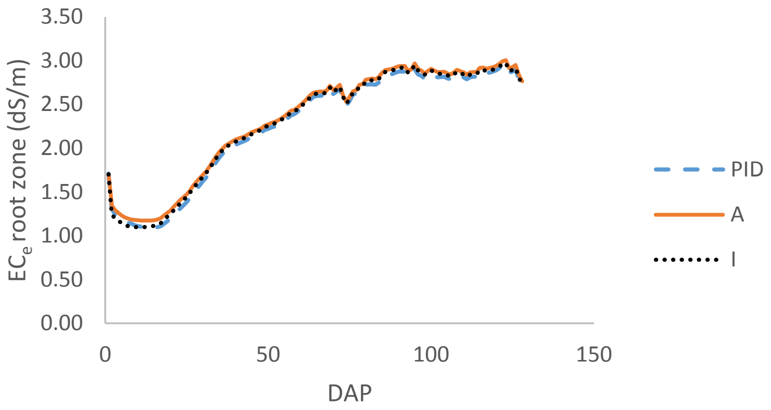


Figure 3-19 **Simulated soil salinity in the root zone of wheat for different scheduling scenarios – Kharif 2015 Week 10**

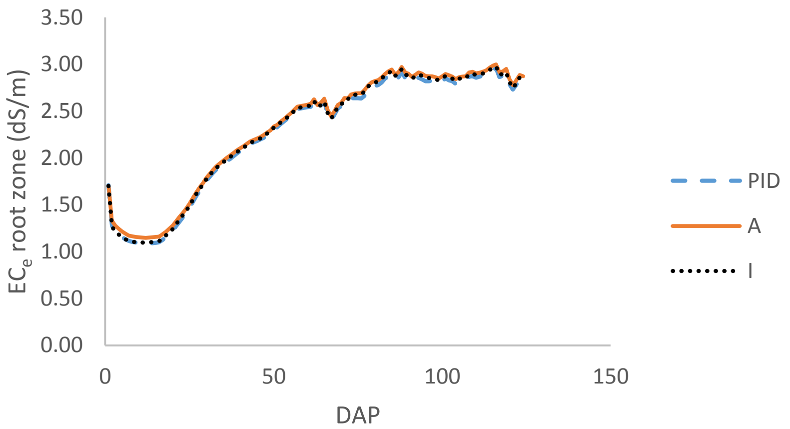


Figure 3-20 **Simulated soil salinity in the root zone of wheat for different scheduling scenarios – Kharif 2015 Week 11**

The effect of soil salinity on the crop yield (biomass) is determined by the EC_e of soil saturated paste in the effective rooting depth. As a result of wheat cultivation, the average EC_e of saturated soil paste in the effective root zone is between 1 dS/m and 2.9 dS/m across all the scheduling scenarios. There is no loss of the crop yield (biomass) as a result of the salinity stress in the root zone as it is below 5.9dS/m, which is the value above which wheat yields are affected.

CHAPTER 4: CONCLUSION AND RECCOMENDATIONS

4.1. Conclusions

In this study, the effects of different planting dates and scheduling scenarios on achievable yield, conjunctive water use, root zone depletion and salt accumulation in the root zone have been studied for both cotton and wheat. This has been achieved by the use of a crop water productivity model, AquaCrop, to simulate the outcomes of using different scheduling scenarios on different planting dates on the parameters stated.

Crop simulations for both cotton and wheat indicate that there is an advantage planting earlier in the season regardless of the scenario of scheduling used. Planting a cotton crop later in the season incurs a loss of between 0.2% and 5.8% in achievable yield while in the case of wheat, the loss is between 11% and 28%. This could be attributed to the rain falling right on time or the temperatures being at the right range that favours crop production when planting is done early.

The production factor that is easy to control is water availability to farmers. It can be supplied on time but other factors, for example, labour, machinery and certified seeds can lead to delay in planting if they are not available on time.

A comparison between achievable yields based on the same planting date for the three scenarios indicate a minimal difference. This shows that the PID schedules perform as well as the ECWA schedules.

The amount of water used to bring the crops to maturity decreases as both cotton and wheat are planted late in the season. For cotton, up to 10% more water is required by the crop planted early in the season while for wheat, it is up to 6% more for the crop planted late in the season. This can be attributed to prevailing weather conditions especially temperature. Cotton crop planted early has its crop development stage coinciding with high Kharif temperatures while for late wheat crop, the overlap between Rabi and Kharif means that temperatures are rising and hence more water is required due to increased evapotranspiration.

Surface flows (water supplied by irrigation) are the main source of water but this water cannot meet the crops' water requirement on its own. It is supplemented by groundwater (from tubewells and capillary rise) and rainfall. Kharif 2014 represents a season when the surface flows are high while Kharif 2015 represents a season when surface flows are low. Simulation indicates that for Kharif 2014, both

Scenario A and Scenario I schedules require more water from tubewells than PID schedules while for Kharif 2015, there is minimal difference between the three scheduling scenarios. For Rabi 2014/2015, there is no need for supplementing available water from surface flows and capillary rise with tubewell water. PID schedules deliver the highest amount of water while Scenario A schedules deliver the least across the three seasons.

Across the three seasons, the impact of capillary rise cannot be ignored. Simulations indicate that capillary rise can contribute between 25 and 47% for cotton and up to 55% for wheat water needs. In a way, capillary rise helps in saving water costs since it is accessed by crops on demand as long as the right conditions are available, that is, the water table is not too deep and there is a presence of driving energy (adequate ET_O).

With regard to root zone depletion, Scenario A causes the most depletion for different planting dates across the three seasons. This is in line with Scenario A delivering the least water throughout the season. Scheduling according to Scenario I causes the least depletion for cotton crop in Kharif 2014 while PID schedules results to the least depletion for Rabi 2014/2015 and Kharif 2015.

Supplementing surface flow with tubewell water and water derived from capillary rise is beneficial to crops as it ensures water requirements are met and hence economical yields are obtained. Quality of deep tubewell water in HBC varies between non-saline to moderately saline while that of the shallow groundwater varies between slightly saline to very saline. This means that whenever water from these sources is used for irrigation, it will bring some amount of salts in the root zone. Salt balance simulations for Kharif 2014 indicate that the water draining from the root zone is able to leach enough salts so that the net flux of salt is negative. Overall, PID schedules causes the most leaching while Scenario A schedules causes the least. Leaching results in the EC_e of the water in the root zone to be lower at the end of the growing period than when planting.

Simulations for Rabi 2014/15 and Kharif 2015 paints a very different picture. There is build- up of about 2 ton/ha for Rabi 2014/15 and about 7 ton/ha for Kharif 2015. This reversal from Kharif 2014 can be attributed to the high flux of water from shallow groundwater table into the root zone via capillary rise. None of the three scenarios of scheduling has any substantial difference with another as the average salt flux is similar. This has resulted in the value of EC_e of water in the root zone at the end of the growing season being higher than the value of EC_e when planting, raising from about 1.7 dS/m to about 3 dS/m.

The build-up of salt in the soil profile in Rabi 2014/ 2015 and Kharif 2015 can be attributed to less surface flows being delivered for irrigation. The deficit is supplemented with water that ranges between slightly saline to highly saline hence high salt build-up.

Although cotton and wheat are classified as tolerant and moderately sensitive to soil salinity respectively, continued salt build-up into the root zone will start affecting them. Flushing flows and lowering of the groundwater is required to prevent a situation where the soil cannot support them due to salinity. Since some farmers are known to occasionally incorporate vegetables (potatoes, onions, pepper), rice and fodder in their rotations, the heavy flux of salt in the root zone would affect their productivity since they fall in the salt sensitive class of crops

The best scenario of scheduling is scheduling according to Scenario I. This is because it allows for equitable distribution of water among the farmers and from this study, it performs marginally well in terms of achievable yield for cotton, does not require as much groundwater (tubewell), has lower depletion and the salt accumulation than Scenario A. While PID schedules are reasonable in terms of these factors, they should however be replaced as they cause a higher inequity in water distribution among farmers.

4.2. Recommendations for future research

Since calibration of the AquaCrop was not done due to limited data availability, it is recommended that it should be done to determine if the conditional and conservative parameters applied in this research hold true. Detailed soil investigations should be conducted to include the actual EC_e of saturated soil paste, fertility levels and the actual water contents at saturation, field capacity and saturation for use in future studies and model calibration.

Long term simulation of the salt accumulation in the root zone should be done as this study only capture the events of two seasons. It appears that there is an offset in the amount of salts accumulated as a result of wheat production being drained by the water supplied for cotton production. It is not possible to know the exact behaviour in terms of salts accumulation by just looking at the results of two season hence the need for longer period of study.

Since there are other crops grown in the region, for example, rice, fodder, sugarcane and vegetables, investigations on how the ECWA model schedules affect these crops should be investigated.

REFERENCES

Agriculture Department. (2014). *Land Utilization Statistics*. Retrieved from http://www.agripunjab.gov.pk/overview%20new.

Ahmad, B., & Baksh, K. (2015). *Profitability of vegetable cultivation: Pakistan Agriculture Overview*. Retrieved from http://www.pakissan.com/english/agri.overview/profitability.of.vegetable.cultivation.shtml.

Akram, Z., Hussain, S., Mansoor, M., Afzal, M., Waqar, A., & Shabbir, I. (2014). Soil Fertility and Salinity Status of Muzaffargarh District, Punjab Pakistan. *Universal Journal of Agricultural Research, 2*(7), 242-249. doi: 10.13189/ujar.2014.020703.

Ali, H., Afzal, M. N., Ahmad, S., & Muhammad, D. (2009). Effect of cultivars and sowing dates on yield and quality of Gossypium hirsutum L. crop. *J. of Food, Agriculture and Environment, 7*(3&4), 244-247.

Ali, M., Ali, L., Sattar, M., & Ali, M. A. (2010). Response of seed cotton yield to various plant populations and planting methods. *J. Agric. Res, 48*(2).

Allen, R. G., Pereira, L. S., Smith, M., Raes, D., & Wright, J. L. (2005a). FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. *Journal of irrigation and drainage engineering, 131*(1), 2-13. doi:10.1061/(ASCE)0733-9437.

Allen, R. G., Walter, I. A., Elliott, R., Howell, T., Itenfisu, D., & Jensen, M. (Eds.). (2005b). *The ASCE standardized reference evapotranspiration equation: ASCE-EWRI Standardization of Reference Evapotranspiration Task Committe Report*. Reston, VA: ASCE Reston.

Anwar, A. A., & Haq, Z. U. (2013). An old–new measure of canal water inequity. *Water International, 38*(5), 536-551. doi: 10.1080/02508060.2013.832124.

Arain, G. N. (2012). *Cotton Cultivation in Pakistan*. Valley Irrigation Pakistan Limited. Lahore, Pakistan. Retrieved from http://www.valleyirrigationpakistan.com/wp-content/uploads/2012/09/COTTON-CULTIVATION-IN-PAKISTAN.pdf.

Asif, M. (2013). *Climatic Change, Irrigation Water Crisis and Food Security in Pakistan.* Masters Thesis, Uppsala University, Uppasala, Sweden.

Aslam, M. (1998). *Waterlogging and salinity management in the Sindh Province, Pakistan. Supplement IA. Improved water management practices for the rice-wheat cropping systems in Sindh Province, Pakistan*. International Water Management Institute.

Aslam, M., & Anwar, A. A. (2014). Surface Water Issues. *Pakistan Water Dialogue Project*. Lahore, Pakistan.

Aslam, M., Hamid, A., Hussain, A., & Tabassam, M. (1999). *Soil salinity-sodicity and land use suitability in the Fordwah Eastern Sadiqia (South) irrigated area* (No. H024896) International Water Management Institute.

Ayers, R., & Westcot, D. (1985). Water quality for agriculture. FAO Irrigation and drainage paper 29 (Rev. 1).Rome, Italy:FAO.

Bandaragoda, D. J., & ur Rehman, S. (1995). *Warabandi in Pakistan's canal irrigation systems: Widening gap between theory and practice*. Colombo, Sri Lanka: International Irrigation Management Institute.

Banuri, T. (1998). Pakistan: environmental impact of cotton production and trade. *mimeographed), IISD, Canada*.

Bhutta, M. N. (1990). *Effect of varying discharges on the equity of water distribution in the irrigation system.* Ph. D dissertation, Center of Excellence in Water Resources Engineering, University of Engineering and Technology, Lahore.

Bhutta, M. N., & Smedema, L. K. (2007). One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: a historical review. *Irrigation and Drainage, 56*(S1), S81-S90.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., . . . Burger, P. (2003). An overview of the crop model STICS. *European Journal of agronomy, 18*(3), 309-332. doi: 10.1016/S1161-0301(02)00110-7.

Bureau of Statistics. (2012). *Punjab Development Statistics.* Retrieved from http://bos.gop.pk/?q=system/files/Development-Statistics-2012.pdf.

Byerlee, D., Hobbs, P. R., Khan, B., Majid, A., Akhtar, M., & Hashmi, N. I. (1986). *Increasing wheat productivity in the context of Pakistan's irrigated cropping systems: A view from the farmers' field*. Islamabad: Pakistan Agriculturatl Research Council (PARC)/ CIMMYT, Collaborative Program.

Cai, X., & Rosegrant, M. W. (2003). 10 World Water Productivity: Current Situation and Future Options. *Water productivity in agriculture: limits and opportunities for improvement, 1*, 163.

Carter, T. R. (2013). Agricultural Impacts: Multi-model yield projections. [News and Views]. *Nature Clim. Change, 3*(9), 784-786. doi: 10.1038/nclimate1995.

Condom, N., Kuper, M., Marlet, S., Valles, V., & Kijne, J. (1999). Salinization, alkalinization and sodification in Punjab (Pakistan): Characterization of the geochemical and physical processes of degradation. *Land Degradation & Development, 10*(2), 123-140.

Condon, M., Kriens, D., Lohani, A., & Sattar, E. (2014). Challenge and response in the Indus Basin. *Water Policy, 16*(S1), 58-86.

Cotton Incorporated. (2015). *Montly Economic Letter.* Retrieved from http://www.cottoninc.com/corporate/Market-Data/MonthlyEconomicLetter/pdfs/English-pdf-charts-and-tables/World-Cotton-Production-Exp.pdf.

Cullmann, J., Mishra, V., & Peters, R. (2006). Flow analysis with WaSiM-ETH? model parameter sensitivity at different scales. *Advances in Geosciences, 9*, 73-77.

Curtis, B. C., Rajaram, S., & Gómez, M. H. (2002) Wheat in the world. Bread wheat improvement and production. *FAO: Plant Production and Protection Series*. Rome, Italy: FAO.

De Vries, T. T. (2000). Technical and social economic factors influencing the performance of bed and furrow irrigation method-. Lahore, Pakistan: International Water Management Institute.

De Vries, T. T. (2014). Equitable Canal Water Allocation, Deliverable B1 *Internal Report, Revitalising Irrigation in Pakistan*. University of Canterbury, New Zealand.

De Vries, T. T., & Anwar, A. A. (2015). *Equitable Canal Water Allocation*. Paper presented at the EWRI 2015, World Environmental & Water Resources Congress, Austin, Texas.

Directorate of Agriculture. (2015). *Cropping Schedule Surveys.* Retrieved from http://www.crs.agripunjab.gov.pk.

FAO. (2011). *Indus Basin*. Retrieved from http://www.fao.org/nr/water/aquastat/basins/indus/index.stm.

FAO. (2013a). *AquaCrop.* Retrieved from http://www.fao.org/nr/water/infores_databases_aquacrop.html.

FAO. (2013b). *CropWat.* Retrieved from http://www.fao.org/nr/water/infores_databases_cropwat.html.

FAO. (2015). *Crop Water Information: Cotton.* Retrieved from http://www.fao.org/nr/water/cropinfo_cotton.html.

Fowler, H. J., & Archer, D. R. (2005). Hydro-climatological variability in the Upper Indus Basin and implications for water resources. *Regional Hydrological Impacts of Climatic Change—Impact Assessment and Decision Making, 295*, 131-138.

Fujisaka, S., Morris, M., Hobbs, P., Sharma, H., Singh, R., Chaudhary, M., & Dhiman, S. (1992). *Wheat and Rice in Karnal and Kurukshetra Districts, Haryana, India: Farmers' Practices, Problems, and an Agenda for Action*. Mexico, D.F: CIMMYT.

George, R. J., & Hazlewood, S. P. (2015). *Groundwater, Temperature and Salinity*. Civil and Natural Resources Engineering. University of Canterbury. Christchurch, New Zealand.

Gommes, R. (2001). *Agro-meteorological models and remote sensing for crop monitoring and forecasting in Asia and the Pacific.* Paper presented at the Report of the FAO Asia-Pacific Conference.

Hillel, D. (1977). *Computer simulation of soil-water dynamics: a compendium of recent work*: International Development Research Centre, Ottawa, Canada.

Hobbs, P. R., Sayre, K. D., & Ortiz-Monasterio, I. (1998). Increasing wheat yields sustainability through agronomic means. CIMMYT *NRG Paper 98-01*.

Hunink, J., Vila, M., & Baille, A. (2011). *REDSIM: Approach to soil water modelling*. Retrieved from http://www.futurewater.nl/wp-content/uploads/2012/04/Approach-to-soil-water-modelling-for-REDSIM.pdf.

Hussain, I., Hussain, Z., Sial, M. H., Akram, W., & Farhan, M. F. (2011). Water balance, supply and demand and irrigation efficiency of Indus basin. *Pakistan Economic and Social Review*, 13-38.

IndexMundi. (2015a). *Cotton Yield by Country in KG/HA.*Retrieved from http://www.indexmundi.com/agriculture/?commodity=cotton&graph=yield.

IndexMundi. (2015b). *Wheat Yield by Country in MT/HA.* Retrieved from http://www.indexmundi.com/agriculture/?commodity=wheat&graph=yield.

IndexMundi. (2016a). *Cotton Monthly Price - Pakistan Rupee per Pound.* Retrieved from http://www.indexmundi.com/commodities/?commodity=cotton&months=60&currency=pkr.

IndexMundi. (2016b). *Wheat Monthly Price - Pakistan Rupee per Metric Ton.* Retrieved from http://www.indexmundi.com/commodities/?commodity=wheat&months=12&currency=pkr.

Ines, A. V. M., Droogers, P., W, M. I., & Das Gupta, A. (2001). *Crop growth and soil water balance modeling to explore water management options* (Vol. 22). Colombo, Sri Lanka: International Water Management Institute.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L., . . . Ritchie, J. T. (2003). The DSSAT cropping system model. *European journal of agronomy, 18*(3), 235-265.

Jurriëns, R., Mollinga, P., & Wester, P. (1996). *Scarcity by design: Protective irrigation in India and Pakistan*. Wageningen Agricultural University, The Netherlands: International Institute For Land Reclamation And Improvement.

Kahlown, M.A., Iqbal, M., & Skogerboe, G. (1998). Waterlogging, salinity and crop yield relationships. Lahore, Pakistan: WAPDA. Mona Reclamation Experimental Project; International Irrigation Management Institute (IIMI). Pakistan National Program.

Kahlown, M. A., Raoof, A., Zubair, M., & Kemper, W. D. (2007). Water use efficiency and economic feasibility of growing rice and wheat with sprinkler irrigation in the Indus Basin of Pakistan. *Agricultural water management, 87*(3), 292-298.

Kalwij, I.M. (1997). *Surface irrigation methods and practices: field evaluation of the irrigation processes for selected basin irrigation systems during Rabi 1995-96 season.* Punjab, Pakistan: International Water Management Institute.

Kalwij, I. M., Mirza, Z., Amin, M., & Hameed, A. (1999). Disseminating the bed-and-furrow irrigation method for cotton cultivation in the Hakra-4-R Distributary in collaboration with the Water Users Federation: International Water Management Institute.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., . . . Hochman, Z. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy, 18*(3), 267-288.

Kijne, J. W., & Kuper, M. (1995). Salinity and sodicity in Pakistan's Punjab: A threat to sustainability of irrigated agriculture? *International Journal of Water Resources Development, 11*(1), 73-86. doi: 10.1080/07900629550042470.

Kirda, C. (2002). Deficit irrigation scheduling based on plant growth stages showing water stress tolerance *Deficit irrigation practices*. Cukuroya University, Adana, Turkey.

Kumar, P., Sarangi, A., Singh, D. K., & Parihar, S. S. (2014). Evaluation of AquaCrop model in predicting wheat yield and water productivity under irrigated saline regimes. *Irrigation and Drainage, 63*(4), 474-487.

Laghari, K. Q. (2009). *Perceptive Research on Irrigation Scheduling and Water Management.* Doctoral dissertation, Mehran University of Engineering & Technology, Jamshoro.

Latif, N., Khan, M., & Ali, T. (2008). Effects of soil compaction caused by tillage and seed covering techniques on soil physical properties and performance of wheat crop. *Soil and Environment, 27*(2), 185-192.

Malhotra, S. (1982). *Warabandi system and its infrastructure*: Central Board of Irrigation and Power New Delhi, India.

Martin, E. C. (2001) Methods of Measuring for Irrigation Scheduling. *Arizona Water Series: Vol. 30* (pp. 51). Tucson: The University of Arizona.

Meerbach, P. D. B. J. (1997). *Relating farmers' practices to cotton yields in the South-Punjab, Pakistan*: International Water Management Institute.

Murray-Rust, H. (2002). Conjunctive water use and conjunctive water management *Conjunctive Water Management-for Sustainable irrigated Agriculture in South* (pp. 19). Colombo, Sri Lanka: International Water Management Institute.

Naheed, G., & Rasul, G. (2010a). Projections of crop water requirement in Pakistan under global warming. *Pakistan Journal of Meteorology, 7*(13), 45-51.

Naheed, G., & Rasul, G. (2010b). Recent water requirement of cotton crop in Pakistan. *Pakistan Journal of Meteorology, 6*(12).

Naz, H. (2010). *The Environment of Pakistan*. Retrieved from http://ourpgs.com/books/THE%20ENVIRONMENT%20OF%20PAKISTAN%20by%20huma%20naz/UNIT.2.Climate%20of%20Pakistan.pdf.

Oteng-Darko, P., Yeboah, S., Addy, S., Amponsah, S., & Danquah, E. O. (2013). Crop modeling: a tool for agricultural research—a review. *J Agric Res Dev, 2*(1), 1-6.

Pakistan Bureau of Statistics. (1998). *Area and Population of Administrative Units*. Retrieved from http://www.pbs.gov.pk/content/area-population-aadministrative-units.

Population Welfare Department. (2013). *Population Situation of Punjab*. Retrieved from http://www.pwd.punjab.gov.pk/overview.

Porter, J. R., & Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy, 10*(1), 23-36. doi: 10.1016/S1161-0301(98)00047-1.

Programe Monitoring And Implementation Unit (PIMU). (2015). *Channel Search.* Retrieved from http://irrigation.punjab.gov.pk/livedata.aspx.

Qureshi, A.S (2014). Conjunctive Water Management in the Fixed Rotational Canal System: A Case Study from Punjab Pakistan. *Irrigat Drainage Sys Eng, 3*(122), 2.

Qureshi, A. S., & Fatima, A. (2012). Sustaining irrigated agriculture for food security: a perspective from Pakistan. *On the Occasion of World Water Day*.

Qureshi, A. S., McCornick, P. G., Qadir, M., & Aslam, Z. (2008). Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agricultural Water Management, 95*(1), 1-10. doi: 10.1016/j.agwat.2007.09.014.

Qureshi, A. S., Shah, T., & Akhtar, M. (2003). *The groundwater economy of Pakistan* (Vol. 64). Lahore, Pakistan: International Water Management Institute.

Qureshi, R. H., & Barrett-Lennard, E. G. (1998). *Saline agriculture for irrigated land in Pakistan: a handbook*: Australian Centre for International Agricultural Research (ACIAR).

Raes, D., & Deproost, P. (2003). Model to assess water movement from a shallow water table to the root zone. *Agricultural Water Management, 62*(2), 79-91.

Raes, D., Steduto, P., Hsiao, T. C., & Fereres, E. (2009a). AquaCrop–The FAO crop model to simulate yield response to water. *FAO Land and Water Division, FAO, Rome*.

Raes, D., Steduto, P., Hsiao, T. C., & Fereres, E. (2009b). AquaCrop the FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal, 101*(3), 438-447. doi: 10.2134/agronj2008.0140s.

Raes, D., Van Goidsenhoven, B., Goris, K., Samain, B., De Pauw, E., El Baba, M., . . . De Nys, E. (2001). BUDGET, a management tool for assessing salt accumulation in the root zone under irrigation.

Rhoades, J., Kandiah, A., & Mashali, A. (1992). The use of saline waters for crop production-FAO irrigation and drainage paper 48. *FAO, Rome, 133*.

Richardson, B. C., Roberts, D. C., & Saalberg, H. J. (1979). *Limitations on the use of mathematical models in transportation policy analysis*. University of Michigan: UMI Research Press.

Savary, S., & Willocquet, L. (2014). Simulation Modeling in Botanical Epidemiology and Crop Loss Analysis. APSnet The Plant Health Instructor *http://www. apsnet. org/edcenter/advanced/topics/BotanicalEpidemiology/Pages/default. aspx,* doi, 10.1094/PHI-A-2014-314-01.

Shah, S. M. S., Maan, Z. M., & Sarwar, M. K. (2011). Impact of the Alternative Lining of Water Course on Cost and Efficiency. *Science, Technology and Development, 30*(4), 31-38.

Sharma, D., & Tyagi, N. (2004). On-farm management of saline drainage water in arid and semi-arid regions. *Irrigation and drainage, 53*(1), 87-103. doi: 10.1002/ird.115

Singh, A. K. (1994). Crop Growth Simulation Models. *IASRI, New Delhi*, 497-509.

Singh, R., Kroes, J., Van Dam, J., & Feddes, R. (2006a). Distributed ecohydrological modelling to evaluate the performance of irrigation system in Sirsa district, India: I. Current water management and its productivity. *Journal of Hydrology, 329*(3), 692-713. doi: 10.1016/j.jhydrol.2006.03.037.

Singh, R., Van Dam, J., & Feddes, R. A. (2006b). Water productivity analysis of irrigated crops in Sirsa district, India. *Agricultural Water Management, 82*(3), 253-278. doi: 10.1016/j.agwat.2005.07.027.

Skogerboe, G. W., Aslam, M., Khan, M. A., Mahmood, K., Mahmood, S., & Khan, A. H. (1999). Inflow-outflow channel losses and canal lining cost-effectiveness in the Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project. Lahore, Pakistan: International Water Management Institute.

Sohag, M. A., & Mahessar, A. A. (2004). *Telemetry System in the Irrigation Network.* Paper presented at the National Conference on Emerging Technologies.

Soomro, U. A., Rahman, M. U., Odhano, E. A., Gul, S., & Tareen, A. Q. (2009). Effects of sowing method and seed rate on growth and yield of wheat (Triticum aestivum). *World Journal of Agricultural Sciences, 5*(2), 159-162.

Steduto, P., Hsiao, T. C., & Fereres, E. (2007). On the conservative behavior of biomass water productivity. *Irrigation Science, 25*(3), 189-207.

Steduto, P., Hsiao, T. C., Fereres, E., & Raes, D. (2012). Crop yield response to water. *FAO irrigation and drainage paper, 66*.

Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal, 101*(3), 426-437. doi: 10.2134/agronj2008.0139s.

Steduto, P., Raes, D., Hsiao, T. C., Fereres, E., Heng, L. K., Howell, T. A., . . . Izzi, G. (2009). Concepts and applications of AquaCrop: the FAO crop water productivity model *Crop Modeling and Decision Support* (pp. 175-191): Springer Berlin Hiedelberg.

Stöckle, C. O., Donatelli, M., & Nelson, R. (2003). CropSyst, a cropping systems simulation model. *European Journal of Agronomy, 18*(3), 289-307. doi: 10.1016/S1161-0301(02)00109-0.

Sufi, A. B. (2011). *Irrigation water pricing and its sustainability in Pakistan*. Paper presented at the Pakistan Engineering Conference, 71st Annual Session Proceedings, Islamabad.

The Statistical Portal. (2015a). *Leading 10 wheat producers worldwide in 2013/2014 (in 1,000 metric tons).* Retrieved from http://www.statista.com/statistics/267268/production-of-wheat-worldwide-since-1990.

The Statistical Portal. (2015b). *World's 10 leading cotton producing countries in 2013/2014 (in 1,000 metric tons).* Retrieved from http://www.statista.com/statistics/263055/cotton-production-worldwide-by-top-countries.

Ul Haq, A. (1998). *Case study of the Punjab Irrigation Department: consultancy report*. Lahore, Pakistan: International Water Management Institute.

van Dam, J. C., Groenendijk, P., Hendriks, R. F., & Kroes, J. G. (2008). Advances of modeling water flow in variably saturated soils with SWAP. *Vadose Zone Journal, 7*(2), 640-653. doi: 10.2136/vzj2007.0060.

Waheed-uz-Zaman, & Hamid, A. (1998). Pre-takeover comparative performance of water users organizations of Hakra 4-R Distributary, Punjab, Pakistan: International Water Management Institute.

Wolters, W., & Bhutta, M. N. (1997). *Need for Integrated Irrigation and Drainage Management: Example from Pakistan.* Paper presented at the Fortieth Anniversary of ILRI, Thirty-Fifth Anniversary of ICLD. 'Towards Integration of Irrigation and Drainage Management', Wageningen Department(s) International Institute for Land Reclamation and Improvement.

World Population Review. (2014). *Pakistan Population 2014*. Retrieved from http://worldpopulationreview.com/countries/pakistan-populatio.

APPENDIX A - METEOROLOGICAL DATA

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
17/04/2014	1.72	21.81	33.14	26.34	59.64	23.04	0.0	5.5
18/04/2014	1.20	18.32	30.38	36.64	87.80	23.82	1.0	4.8
19/04/2014	0.78	17.26	31.54	29.29	94.80	24.60	0.0	4.7
20/04/2014	0.80	18.55	33.12	26.79	81.30	24.00	0.0	4.7
21/04/2014	0.76	19.78	32.96	28.95	70.78	23.69	0.0	4.7
22/04/2014	0.64	20.55	33.07	23.61	71.00	23.92	0.0	4.7
23/04/2014	0.36	19.05	35.14	21.30	79.40	24.14	0.0	4.5
24/04/2014	0.54	21.56	38.08	17.03	64.06	22.91	0.0	4.6
25/04/2014	1.10	25.03	37.77	20.75	56.55	22.78	0.0	5.4
26/04/2014	0.60	24.84	37.48	14.41	50.29	22.69	0.0	4.7
27/04/2014	0.50	21.31	39.04	13.43	65.34	22.60	0.0	4.6
28/04/2014	0.48	20.80	40.79	9.54	67.43	22.48	0.0	4.6
29/04/2014	0.48	21.14	42.06	7.99	60.49	24.55	0.0	4.8
30/04/2014	0.44	23.48	43.07	8.16	48.70	24.21	0.0	4.8
1/05/2014	0.55	24.48	42.91	8.29	55.23	21.55	0.0	4.7
2/05/2014	0.50	23.98	42.99	8.23	51.97	22.88	0.0	4.7
3/05/2014	0.69	25.49	37.14	25.27	59.44	20.52	0.0	4.7
4/05/2014	0.87	27.60	37.43	22.15	53.03	19.50	0.0	4.8
5/05/2014	0.51	23.37	36.84	28.38	65.84	21.54	0.0	4.6
6/05/2014	0.47	24.11	37.67	24.08	66.48	20.10	0.0	4.4
7/05/2014	0.48	24.15	38.99	18.20	59.30	21.61	0.0	4.6
8/05/2014	1.05	24.89	39.83	13.26	57.01	19.01	0.2	5.0
9/05/2014	0.52	21.66	37.26	20.16	67.00	21.53	0.0	4.5
10/05/2014	1.07	21.69	35.63	21.55	84.80	18.82	6.4	4.6
11/05/2014	0.55	20.78	34.90	26.45	81.10	23.13	4.9	4.7
12/05/2014	0.94	19.40	33.99	28.45	89.70	21.25	0.7	4.7
13/05/2014	1.20	19.60	28.68	58.61	92.20	19.36	15.6	4.0
14/05/2014	0.74	19.85	30.68	46.18	90.60	20.33	0.0	4.2
15/05/2014	0.62	21.36	34.90	32.78	93.00	23.08	11.7	4.8
16/05/2014	0.59	20.80	33.84	40.13	90.40	23.30	4.7	4.8
17/05/2014	1.15	19.83	32.32	55.20	97.30	24.95	24.7	5.1
18/05/2014	0.80	20.12	30.55	48.43	91.10	24.38	4.2	4.8
19/05/2014	0.31	21.59	33.95	35.16	92.80	21.50	0.0	4.4
20/05/2014	0.60	23.45	35.34	28.52	91.30	23.87	0.0	5.1
21/05/2014	0.42	23.38	37.76	24.60	82.20	23.84	0.0	5.0
22/05/2014	0.82	25.07	40.80	13.58	69.49	22.94	0.0	5.4
23/05/2014	0.95	25.21	40.36	18.55	57.76	20.67	0.0	5.2
24/05/2014	0.64	23.72	39.80	11.69	58.21	21.17	0.0	4.8
25/05/2014	0.73	25.06	39.54	16.79	53.01	19.19	0.0	4.7
26/05/2014	0.50	24.20	40.73	14.05	59.67	20.67	0.0	4.6
27/05/2014	0.48	26.05	40.92	15.54	54.83	19.59	0.0	4.5

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
28/05/2014	0.74	27.55	43.58	12.22	51.29	18.94	0.0	4.9
29/05/2014	0.59	27.09	44.07	15.80	53.59	17.97	0.0	4.5
30/05/2014	0.97	30.28	40.92	20.47	53.39	17.09	0.0	4.9
31/05/2014	0.70	27.77	41.76	18.54	52.26	16.20	0.0	4.4
1/06/2014	1.24	28.86	40.36	27.63	57.62	17.10	0.0	5.1
2/06/2014	0.62	25.84	41.36	17.23	67.06	18.00	0.0	4.5
3/06/2014	0.43	25.40	42.60	15.47	71.38	17.90	0.0	4.2
4/06/2014	0.60	27.86	45.01	12.05	54.10	17.36	0.0	4.5
5/06/2014	0.44	27.33	44.92	13.10	68.31	17.18	0.0	4.3
6/06/2014	0.61	30.37	45.31	11.82	54.15	17.36	0.0	4.6
7/06/2014	0.51	28.64	44.84	10.77	59.59	16.46	0.0	4.2
8/06/2014	0.64	29.79	45.93	8.44	48.95	17.25	0.0	4.6
9/06/2014	0.76	28.25	44.98	8.64	53.54	17.28	0.0	4.7
10/06/2014	0.82	27.02	44.99	7.90	61.54	17.25	0.0	4.8
11/06/2014	0.84	30.54	42.69	14.52	43.56	16.49	0.0	4.7
12/06/2014	1.13	30.46	40.61	27.06	50.24	15.34	0.0	4.7
13/06/2014	1.12	29.63	40.23	26.82	52.36	16.10	0.0	4.8
14/06/2014	1.18	31.37	41.00	28.85	59.24	16.06	0.0	4.9
15/06/2014	1.10	31.86	41.27	27.42	56.73	16.60	0.0	5.0
16/06/2014	1.08	32.09	43.12	24.41	51.69	16.82	0.0	5.1
17/06/2014	1.04	33.26	43.14	22.01	48.09	15.95	0.0	5.0
18/06/2014	1.21	32.85	41.92	23.06	53.50	16.13	0.0	5.1
19/06/2014	0.85	32.41	41.90	25.66	61.62	15.52	0.0	4.5
20/06/2014	0.87	30.33	43.22	19.25	76.18	16.35	0.0	4.7
21/06/2014	1.18	28.14	41.50	23.87	71.22	15.63	0.0	4.8
22/06/2014	1.25	25.14	36.32	46.50	81.00	13.14	1.9	3.8
23/06/2014	0.81	25.42	36.94	37.71	88.50	13.54	3.6	3.6
24/06/2014	1.08	28.87	38.44	37.80	70.52	14.19	4.6	4.2
25/06/2014	1.03	27.67	38.66	23.14	65.43	14.80	0.0	4.4
26/06/2014	0.77	23.13	33.74	51.39	94.10	10.70	24.8	2.8
27/06/2014	0.80	28.07	37.86	46.05	82.70	15.45	0.0	4.0
28/06/2014	0.90	29.49	39.64	37.09	70.61	17.86	0.0	4.8
29/06/2014	0.82	30.84	38.29	38.17	66.91	17.03	0.0	4.5
30/06/2014	1.03	29.82	37.72	39.83	65.13	15.77	0.0	4.4
1/07/2014	0.93	28.87	36.59	44.37	71.24	12.89	0.0	3.7
2/07/2014	0.71	24.66	33.86	60.80	94.20	18.40	29.2	4.2
3/07/2014	0.65	27.66	34.97	52.05	89.60	15.77	0.0	3.8
4/07/2014	0.67	26.84	36.34	48.72	81.10	16.13	0.0	4.0
5/07/2014	0.62	30.40	37.91	42.36	75.68	16.92	0.0	4.3
6/07/2014	0.70	28.32	37.28	39.17	72.20	16.24	0.0	4.1
7/07/2014	0.60	28.91	40.10	30.30	77.43	18.04	0.0	4.5
8/07/2014	0.84	31.17	39.98	29.66	78.27	19.16	0.0	5.0

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
9/07/2014	0.83	30.99	40.44	26.95	68.03	19.30	0.0	5.0
10/07/2014	0.80	30.56	41.41	18.38	67.76	20.16	0.0	5.2
11/07/2014	0.75	29.34	41.49	22.77	68.94	19.55	0.0	5.0
12/07/2014	0.68	28.57	41.66	27.06	73.89	19.70	0.0	4.9
13/07/2014	0.72	30.39	41.89	26.41	79.94	19.48	0.0	5.0
14/07/2014	0.81	31.56	41.44	29.42	70.02	18.65	0.0	5.0
15/07/2014	0.62	31.07	41.85	26.71	69.08	18.72	0.0	4.8
16/07/2014	0.82	31.95	41.22	32.83	67.07	17.82	0.0	4.8
17/07/2014	0.64	25.87	35.40	57.36	98.60	14.15	9.4	3.5
18/07/2014	0.66	25.47	35.74	44.14	89.30	19.55	0.2	4.5
19/07/2014	0.83	28.08	36.30	55.14	86.90	16.96	0.0	4.2
20/07/2014	0.87	28.11	36.54	56.06	80.30	16.56	0.0	4.2
21/07/2014	0.58	30.08	38.70	34.19	86.20	18.44	0.0	4.5
22/07/2014	0.65	29.93	39.03	34.59	77.81	18.40	0.0	4.6
23/07/2014	0.61	29.11	39.70	39.52	87.60	18.94	0.0	4.7
24/07/2014	0.87	29.90	37.76	42.00	74.66	15.45	0.0	4.2
25/07/2014	0.83	28.35	37.37	40.71	74.11	19.08	0.0	4.7
26/07/2014	0.79	27.95	38.34	41.15	77.84	19.16	0.0	4.7
27/07/2014	0.87	29.25	38.23	43.64	83.00	14.69	0.0	4.0
28/07/2014	0.90	27.58	36.58	53.11	85.40	13.36	0.1	3.6
29/07/2014	0.80	25.79	30.37	74.97	95.80	6.84	4.8	1.9
30/07/2014	0.56	26.41	34.27	58.57	96.40	14.73	0.0	3.5
31/07/2014	0.56	27.70	36.94	52.91	94.20	19.08	0.0	4.5
1/08/2014	0.71	28.66	37.17	47.47	93.90	16.31	0.0	4.1
2/08/2014	0.64	28.18	36.23	56.32	92.10	16.13	0.0	3.9
3/08/2014	0.81	28.77	38.06	46.61	78.82	19.44	0.0	4.8
4/08/2014	0.88	28.27	37.77	44.76	78.68	19.12	0.0	4.7
5/08/2014	0.87	29.66	37.98	43.40	69.59	18.11	0.0	4.6
6/08/2014	0.62	29.42	38.09	46.51	72.40	17.79	0.0	4.4
7/08/2014	0.75	29.75	37.93	40.97	74.73	18.65	0.0	4.6
8/08/2014	0.80	28.50	36.95	47.47	99.90	16.46	0.3	4.1
9/08/2014	0.74	28.40	37.58	48.00	96.40	19.30	0.0	4.7
10/08/2014	0.53	26.99	37.42	47.40	94.70	19.30	0.0	4.5
11/08/2014	0.61	29.73	38.28	41.61	83.20	19.52	0.0	4.7
12/08/2014	0.85	29.59	39.09	35.50	71.89	18.90	0.0	4.8
13/08/2014	1.02	29.54	37.56	38.51	65.26	18.26	0.0	4.7
14/08/2014	1.09	29.03	36.98	43.49	67.12	17.68	0.0	4.6
15/08/2014	1.35	28.41	36.58	40.58	70.05	17.07	0.0	4.7
16/08/2014	0.95	28.13	34.36	42.96	76.41	15.27	0.1	3.9
17/08/2014	0.49	26.71	34.49	49.71	96.10	14.22	0.0	3.4
18/08/2014	0.46	25.07	36.61	38.48	87.90	18.54	0.0	4.1
19/08/2014	0.59	26.31	39.37	34.32	89.00	19.12	0.0	4.5

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
20/08/2014	0.76	27.99	39.55	24.25	89.30	20.20	0.0	4.9
21/08/2014	0.79	26.97	38.84	23.85	68.19	21.60	0.0	5.0
22/08/2014	0.70	26.30	38.00	31.02	70.80	22.54	0.0	5.0
23/08/2014	0.59	25.48	38.08	30.24	80.40	22.43	0.0	4.9
24/08/2014	0.46	25.33	37.73	37.00	93.90	21.50	0.0	4.7
25/08/2014	0.54	28.33	39.29	32.53	85.10	20.96	0.0	4.8
26/08/2014	0.75	28.78	38.19	36.42	65.72	20.85	0.0	4.9
27/08/2014	0.84	22.92	35.74	42.38	100.00	12.32	22.4	3.2
28/08/2014	0.69	22.19	32.81	56.36	100.00	20.27	1.4	4.2
29/08/2014	0.36	25.10	34.49	51.64	100.00	21.28	0.0	4.5
30/08/2014	0.48	25.00	34.70	51.10	100.00	21.50	0.0	4.6
31/08/2014	0.53	25.45	34.97	55.93	100.00	20.09	0.0	4.4
1/09/2014	0.86	25.20	32.38	67.84	100.00	17.90	0.1	3.9
2/09/2014	1.34	24.35	31.47	70.57	100.00	15.84	0.0	3.5
3/09/2014	1.35	24.32	28.87	88.30	100.00	10.44	1.4	2.3
4/09/2014	0.75	23.32	27.49	99.90	100.00	3.42	50.1	0.9
5/09/2014	1.04	23.22	31.14	79.54	100.00	13.25	1.7	2.9
6/09/2014	0.40	23.41	32.66	79.21	100.00	18.51	0.0	3.9
7/09/2014	0.34	24.90	34.00	65.23	100.00	18.40	0.0	3.9
8/09/2014	0.37	25.14	34.24	63.50	100.00	19.26	0.0	4.1
9/09/2014	0.38	24.87	33.41	67.12	100.00	19.80	0.0	4.2
10/09/2014	0.50	26.64	34.69	60.10	100.00	18.04	0.0	4.0
11/09/2014	0.52	25.70	35.27	52.38	100.00	17.18	0.0	3.8
12/09/2014	0.61	26.31	33.49	70.86	100.00	15.63	0.0	3.5
13/09/2014	0.41	24.33	34.64	61.14	100.00	18.33	0.0	3.9
14/09/2014	0.76	25.41	35.47	49.10	100.00	19.70	0.0	4.3
15/09/2014	0.65	24.80	35.53	51.40	100.00	19.98	0.0	4.3
16/09/2014	0.47	26.31	36.99	38.79	100.00	19.91	0.0	4.3
17/09/2014	0.53	25.54	36.66	36.53	100.00	17.82	0.0	3.9
18/09/2014	0.44	24.93	36.54	38.29	100.00	20.09	0.0	4.2
19/09/2014	0.45	25.64	36.94	30.07	100.00	19.91	0.0	4.2
20/09/2014	0.44	23.25	36.88	28.52	100.00	19.19	0.0	3.9
21/09/2014	0.54	23.62	36.45	29.06	98.30	18.94	0.0	3.9
22/09/2014	0.52	24.00	36.40	36.56	100.00	18.76	0.0	3.9
23/09/2014	0.72	23.30	36.49	30.96	100.00	19.62	0.0	4.2
24/09/2014	0.85	22.09	35.27	29.13	82.40	18.87	0.0	4.0
25/09/2014	0.66	23.65	33.75	37.01	86.50	17.90	0.0	3.7
26/09/2014	0.53	22.56	34.63	45.62	100.00	16.42	0.0	3.4
27/09/2014	0.62	23.79	35.58	29.77	100.00	17.14	0.0	3.6
28/09/2014	0.59	23.90	36.30	23.42	77.72	15.56	0.0	3.4
29/09/2014	0.73	23.90	35.99	32.58	89.60	14.33	0.0	3.3
30/09/2014	0.47	22.97	35.52	33.66	100.00	14.91	0.0	3.2

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
1/10/2014	0.53	23.61	36.51	25.00	78.47	14.04	0.0	3.1
2/10/2014	0.33	20.89	35.91	31.22	100.00	14.19	0.0	2.9
3/10/2014	0.35	20.56	37.34	26.36	99.50	15.99	0.0	3.2
4/10/2014	0.43	19.79	37.25	27.30	93.30	16.17	0.0	3.2
5/10/2014	0.50	21.85	37.60	23.69	87.50	16.17	0.0	3.3
6/10/2014	0.37	21.68	35.84	35.80	91.70	15.99	0.0	3.1
7/10/2014	0.35	22.88	36.34	32.29	100.00	15.27	0.0	3.1
8/10/2014	0.77	21.51	34.72	45.95	99.40	13.68	0.0	3.0
9/10/2014	0.45	19.01	32.50	40.96	100.00	14.51	0.0	2.8
10/10/2014	0.34	19.65	33.41	40.00	100.00	14.55	0.0	2.8
11/10/2014	0.38	19.63	34.27	34.05	100.00	15.20	0.0	2.9
12/10/2014	0.41	19.07	33.64	34.46	96.60	14.12	0.0	2.7
13/10/2014	0.80	18.71	33.83	25.94	98.90	13.84	0.0	3.0
14/10/2014	0.55	16.18	23.89	60.34	100.00	6.79	3.6	1.5
15/10/2014	0.42	14.77	27.18	49.75	100.00	14.50	0.1	2.4
16/10/2014	0.29	14.52	29.02	38.69	100.00	15.86	0.1	2.5
17/10/2014	0.32	14.98	29.78	35.56	100.00	16.13	0.0	2.6
18/10/2014	0.24	14.64	31.01	29.74	100.00	15.99	0.0	2.5
19/10/2014	0.38	16.09	32.65	24.80	96.80	15.20	0.0	2.6
20/10/2014	0.30	16.64	33.48	22.06	100.00	14.73	0.0	2.5
21/10/2014	0.28	18.52	34.12	24.18	99.50	14.51	0.0	2.5
22/10/2014	0.32	19.04	33.90	27.84	92.60	14.15	0.0	2.5
23/10/2014	0.27	19.17	33.64	31.62	98.80	13.40	0.0	2.4
24/10/2014	0.51	18.78	33.79	27.91	100.00	12.17	0.0	2.4
25/10/2014	0.37	19.95	31.41	43.68	100.00	10.98	0.0	2.1
26/10/2014	0.30	18.54	32.32	35.21	96.00	11.09	0.0	2.1
27/10/2014	0.25	18.92	31.58	38.43	96.50	10.66	0.0	2.0
28/10/2014	0.48	18.86	32.40	28.45	94.00	11.74	0.0	2.3
29/10/2014	0.61	18.77	30.11	39.58	96.00	11.42	0.0	2.2
30/10/2014	0.37	15.64	29.34	43.01	100.00	11.16	0.0	2.0
31/10/2014	0.30	15.53	29.12	27.68	100.00	11.74	0.0	1.9
1/11/2014	0.26	14.46	30.10	26.60	100.00	12.46	0.0	2.0
2/11/2014	0.26	14.69	31.00	27.85	100.00	11.81	0.0	1.9
3/11/2014	0.56	17.87	31.40	28.13	91.80	11.06	0.0	2.2
4/11/2014	0.39	16.57	27.82	49.44	100.00	9.40	0.0	1.7
5/11/2014	0.26	14.95	28.55	45.55	100.00	9.54	0.0	1.7
6/11/2014	0.34	16.53	29.93	40.94	100.00	9.00	0.0	1.7
7/11/2014	0.43	18.25	29.73	45.85	100.00	8.61	0.0	1.7
8/11/2014	0.71	17.19	26.60	29.40	100.00	7.13	0.0	1.7
9/11/2014	0.62	12.89	27.15	19.88	100.00	10.98	0.0	1.9
10/11/2014	0.56	13.13	27.54	22.62	81.40	10.70	0.0	1.9
11/11/2014	0.31	9.80	27.78	17.78	100.00	10.91	0.0	1.6

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
12/11/2014	0.25	9.55	27.80	16.63	100.00	10.73	0.0	1.5
13/11/2014	0.20	8.85	27.48	17.04	100.00	10.66	0.0	1.4
14/11/2014	0.24	8.33	28.02	16.16	100.00	10.41	0.0	1.5
15/11/2014	0.30	9.32	29.59	13.79	100.00	10.77	0.2	1.6
16/11/2014	0.29	10.47	29.31	11.11	68.96	10.66	0.0	1.5
17/11/2014	0.23	10.04	28.78	14.67	100.00	10.16	0.0	1.4
18/11/2014	0.21	10.07	27.97	19.27	100.00	9.65	0.0	1.4
19/11/2014	0.25	10.37	27.66	16.77	100.00	9.22	0.0	1.4
20/11/2014	0.23	9.64	27.41	19.04	100.00	8.86	0.0	1.3
21/11/2014	0.18	9.51	26.73	22.39	100.00	8.64	0.0	1.3
22/11/2014	0.24	9.61	26.88	25.06	100.00	8.64	0.0	1.3
23/11/2014	0.24	9.79	26.14	23.17	100.00	8.61	0.0	1.3
24/11/2014	0.25	7.09	26.29	18.33	100.00	9.47	0.0	1.3
25/11/2014	0.27	8.35	26.60	16.70	100.00	9.11	0.0	1.3
26/11/2014	0.29	8.83	28.05	16.23	100.00	8.93	0.0	1.4
27/11/2014	0.37	11.37	29.85	27.42	100.00	8.75	0.0	1.5
28/11/2014	0.33	14.48	27.02	37.55	100.00	9.40	0.0	1.5
29/11/2014	0.39	12.04	26.77	42.49	100.00	8.57	0.0	1.4
30/11/2014	0.23	12.90	27.28	36.84	100.00	8.93	0.1	1.3
1/12/2014	0.25	11.48	27.19	30.27	100.00	9.44	0.0	1.4
2/12/2014	0.23	11.15	26.95	34.26	100.00	9.26	0.0	1.3
3/12/2014	0.30	11.67	28.40	28.20	100.00	9.69	0.0	1.4
4/12/2014	0.24	10.93	27.58	34.57	100.00	9.33	0.0	1.3
5/12/2014	0.25	11.21	26.86	36.67	100.00	9.62	0.1	1.3
6/12/2014	0.18	9.42	26.13	27.60	100.00	7.49	0.1	1.1
7/12/2014	0.16	9.25	25.32	31.03	100.00	7.35	0.0	1.1
8/12/2014	0.36	9.68	25.76	24.63	100.00	7.64	0.1	1.3
9/12/2014	0.35	8.23	23.83	23.95	100.00	7.28	0.0	1.2
10/12/2014	0.25	5.96	23.26	21.65	100.00	8.46	0.0	1.1
11/12/2014	0.15	4.52	21.17	25.73	100.00	7.46	0.1	1.0
12/12/2014	0.35	4.30	22.02	22.81	100.00	8.50	0.0	1.2
13/12/2014	0.49	6.85	20.30	37.55	100.00	6.59	0.0	1.1
14/12/2014	0.46	6.42	17.32	100.00	100.00	4.54	0.1	0.7
15/12/2014	0.23	6.48	18.39	73.80	100.00	6.70	0.1	0.9
16/12/2014	0.24	5.34	18.29	60.26	100.00	6.88	0.1	0.9
17/12/2014	0.31	5.14	17.50	68.77	100.00	6.99	0.4	0.9
18/12/2014	0.62	5.00	16.78	79.15	100.00	6.20	0.1	0.9
19/12/2014	0.68	7.94	12.10	100.00	100.00	3.60	0.1	0.6
20/12/2014	0.48	6.98	15.05	74.83	100.00	7.13	0.0	0.9
21/12/2014	0.68	4.25	11.89	100.00	100.00	4.83	0.2	0.6
22/12/2014	0.78	5.01	12.59	87.20	100.00	5.01	0.0	0.7
23/12/2014	0.40	4.60	11.08	100.00	100.00	3.24	0.1	0.6

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
24/12/2014	0.33	4.50	10.10	100.00	100.00	2.24	0.2	0.5
25/12/2014	0.36	5.09	9.86	100.00	100.00	3.46	0.3	0.6
26/12/2014	0.27	3.18	17.38	73.52	100.00	7.17	0.3	0.9
27/12/2014	0.29	1.36	22.89	24.64	100.00	9.40	0.1	1.1
28/12/2014	0.32	4.09	18.20	57.41	100.00	9.18	0.1	1.1
29/12/2014	0.51	3.40	15.97	66.35	100.00	7.82	0.2	1.0
30/12/2014	0.43	3.06	12.04	88.60	100.00	6.05	0.2	0.7
31/12/2014	0.64	3.52	8.30	100.00	100.00	2.74	0.2	0.5
1/01/2015	0.42	5.35	17.98	79.55	100.00	5.98	0.0	0.9
2/01/2015	0.39	7.69	21.60	40.59	100.00	7.89	0.0	1.2
3/01/2015	0.43	7.05	17.82	96.90	100.00	5.26	0.1	0.8
4/01/2015	0.78	7.62	17.28	93.80	100.00	6.12	0.2	0.9
5/01/2015	0.34	8.02	15.62	99.30	100.00	5.48	0.1	0.8
6/01/2015	0.38	6.85	12.41	100.00	100.00	3.03	0.2	0.6
7/01/2015	0.44	5.25	13.05	100.00	100.00	4.25	0.2	0.7
8/01/2015	0.58	5.17	10.10	100.00	100.00	3.03	0.3	0.6
9/01/2015	0.55	6.04	10.36	100.00	100.00	3.46	0.2	0.6
10/01/2015	0.40	5.23	10.77	100.00	100.00	3.89	0.1	0.6
11/01/2015	0.32	2.62	16.41	76.64	100.00	6.81	0.1	0.9
12/01/2015	0.98	5.81	18.14	67.64	100.00	8.10	0.1	1.2
13/01/2015	0.89	7.13	14.86	89.90	100.00	5.62	0.1	0.8
14/01/2015	0.58	8.19	12.66	100.00	100.00	2.20	0.0	0.6
15/01/2015	0.44	6.03	14.21	100.00	100.00	4.47	0.1	0.7
16/01/2015	0.44	3.78	18.44	59.20	100.00	9.00	0.3	1.2
17/01/2015	0.37	4.41	20.88	38.62	100.00	10.80	0.1	1.3
18/01/2015	0.24	5.69	21.04	39.27	100.00	10.34	0.0	1.3
19/01/2015	0.31	6.29	21.72	35.53	100.00	10.16	0.1	1.3
20/01/2015	0.84	8.99	21.93	43.09	100.00	10.16	0.0	1.6
21/01/2015	1.06	11.38	16.62	82.70	100.00	6.02	10.8	1.0
22/01/2015	0.74	9.53	15.54	100.00	100.00	5.40	0.1	0.8
23/01/2015	0.34	7.91	15.63	99.90	100.00	5.69	0.0	0.9
24/01/2015	0.38	6.84	11.79	100.00	100.00	3.93	0.3	0.7
25/01/2015	0.50	7.69	12.76	100.00	100.00	3.96	0.0	0.7
26/01/2015	0.45	6.80	14.74	72.74	100.00	9.04	0.0	1.1
27/01/2015	0.29	2.94	14.28	77.24	100.00	7.06	0.1	0.9
28/01/2015	0.42	2.23	16.96	41.01	100.00	12.10	0.2	1.4
29/01/2015	0.36	4.40	18.61	35.21	100.00	12.28	0.0	1.4
30/01/2015	0.23	3.79	18.97	32.20	100.00	11.92	0.0	1.4
31/01/2015	0.48	5.75	20.92	33.85	100.00	11.92	0.0	1.6
1/02/2015	0.66	8.66	19.92	55.67	100.00	7.82	0.0	1.3
2/02/2015	1.27	11.14	17.84	81.30	100.00	6.41	0.1	1.1
3/02/2015	0.74	9.93	19.36	65.20	100.00	12.89	5.7	1.7

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
4/02/2015	0.36	7.22	20.05	65.81	100.00	12.82	1.3	1.6
5/02/2015	0.34	6.92	20.57	54.47	100.00	12.86	0.7	1.6
6/02/2015	0.62	9.73	21.52	49.82	100.00	13.00	0.1	1.8
7/02/2015	0.89	9.96	21.62	51.86	100.00	11.99	0.0	1.9
8/02/2015	0.69	10.19	19.79	65.24	100.00	13.68	0.0	1.8
9/02/2015	0.16	7.93	10.41	100.00	100.00	0.00	0.0	0.5
10/02/2015	0.51	6.92	20.65	45.77	100.00	13.50	0.1	1.8
11/02/2015	0.40	7.08	22.95	29.16	100.00	15.84	0.0	2.0
12/02/2015	0.35	7.43	23.88	26.96	100.00	15.74	0.0	2.0
13/02/2015	0.67	10.24	28.17	28.81	93.10	14.51	0.0	2.4
14/02/2015	0.47	10.59	25.54	47.77	100.00	15.09	0.0	2.2
15/02/2015	0.73	10.38	26.39	51.08	100.00	13.40	0.0	2.2
16/02/2015	0.99	14.25	25.91	64.09	100.00	12.75	0.2	2.2
17/02/2015	0.64	14.43	23.21	85.50	100.00	8.68	0.0	1.5
18/02/2015	0.46	13.29	22.88	100.00	100.00	5.37	0.1	1.1
19/02/2015	0.87	15.06	26.78	80.40	100.00	8.54	0.1	1.7
20/02/2015	0.92	15.22	22.92	99.90	100.00	8.43	0.0	1.4
21/02/2015	0.74	13.33	23.27	70.13	100.00	12.78	0.0	2.1
22/02/2015	0.60	12.42	25.13	70.02	100.00	12.78	0.1	2.1
23/02/2015	0.73	12.99	26.05	0.32	100.00	10.23	0.1	2.3
24/02/2015	1.12	17.40	26.87	0.32	100.00	6.63	0.2	2.4
25/02/2015	1.34	14.18	22.84	0.32	100.00	16.10	0.9	3.0
26/02/2015	0.53	6.42	21.62	0.32	100.00	16.13	0.2	2.2
27/02/2015	0.47	8.52	21.78	0.39	100.00	14.94	0.0	2.2
28/02/2015	0.91	10.42	21.06	0.32	100.00	10.23	0.0	2.2
1/03/2015	1.23	11.63	15.43	77.15	100.00	3.75	1.5	1.0
2/03/2015	0.74	12.18	18.83	70.24	100.00	10.84	1.2	1.8
3/03/2015	0.60	10.17	16.16	93.90	100.00	0.04	0.4	0.5
4/03/2015	0.56	10.29	22.41	68.84	100.00	15.63	0.8	2.3
5/03/2015	0.87	11.23	17.02	98.50	100.00	4.47	20.6	0.9
6/03/2015	0.60	9.87	20.24	36.71	100.00	13.11	0.2	2.1
7/03/2015	0.65	11.29	21.44	0.32	100.00	9.29	5.9	2.0
8/03/2015	1.11	9.78	21.22	0.32	100.00	14.91	0.1	2.8
9/03/2015	0.62	7.24	18.41	0.32	100.00	16.46	0.0	2.4
10/03/2015	0.44	7.26	22.67	0.32	100.00	17.14	0.0	2.4
11/03/2015	0.39	8.97	23.92	0.32	100.00	16.89	0.0	2.5
12/03/2015	0.33	11.45	24.67	0.32	100.00	14.51	0.0	2.3
13/03/2015	0.50	11.21	25.70	0.32	100.00	14.76	0.0	2.5
14/03/2015	0.78	15.64	22.94	42.92	100.00	10.23	1.2	2.1
15/03/2015	1.08	12.85	20.68	94.90	100.00	4.94	13.3	1.1
16/03/2015	0.50	10.74	22.10	0.32	100.00	14.30	0.1	2.4
17/03/2015	0.72	12.29	21.80	71.31	100.00	15.20	0.1	2.4

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
18/03/2015	0.38	11.22	25.73	57.21	100.00	16.13	0.1	2.6
19/03/2015	0.66	13.83	27.36	44.91	100.00	15.88	0.0	2.9
20/03/2015	0.53	16.10	28.44	32.09	100.00	16.38	0.0	3.0
21/03/2015	0.46	15.95	29.01	0.36	100.00	16.74	0.0	3.0
22/03/2015	0.53	18.27	29.97	0.32	100.00	16.38	0.0	3.1
23/03/2015	0.45	15.75	32.78	0.46	100.00	18.04	0.0	3.2
24/03/2015	0.66	18.94	34.46	42.88	100.00	17.18	0.0	3.6
25/03/2015	1.17	18.00	31.48	8.52	96.20	17.07	0.0	3.9
26/03/2015	0.59	17.56	30.54	17.36	100.00	12.06	0.0	2.7
27/03/2015	0.44	16.89	33.37	42.69	100.00	18.15	0.0	3.5
28/03/2015	0.75	18.13	34.56	0.32	100.00	16.06	0.0	3.6
29/03/2015	0.96	17.65	28.03	0.32	100.00	12.68	0.0	3.1
30/03/2015	0.83	14.77	27.91	55.87	100.00	16.53	0.0	3.1
31/03/2015	0.50	15.78	28.82	47.38	100.00	16.13	0.0	3.0
1/04/2015	0.79	19.11	33.37	24.46	100.00	12.68	0.0	3.1
2/04/2015	1.00	17.78	28.40	64.16	100.00	12.57	3.3	2.7
3/04/2015	0.85	17.31	27.26	71.70	100.00	15.52	8.9	3.0
4/04/2015	0.53	16.70	29.39	54.18	100.00	17.61	0.0	3.3
5/04/2015	0.46	16.82	31.44	31.36	100.00	18.58	0.0	3.5
6/04/2015	1.18	16.94	29.88	47.53	100.00	17.00	14.5	3.6
7/04/2015	0.61	14.37	27.26	49.80	100.00	17.72	0.1	3.2
8/04/2015	0.63	14.78	29.43	49.48	100.00	18.51	0.0	3.5
9/04/2015	0.50	17.51	32.15	38.90	100.00	18.18	0.0	3.6
10/04/2015	0.46	19.03	34.71	26.79	100.00	18.36	0.0	3.7
11/04/2015	0.99	20.49	32.32	32.04	100.00	11.27	3.1	3.0
12/04/2015	0.43	19.30	31.28	29.00	100.00	13.79	0.0	2.9
13/04/2015	0.37	18.30	33.58	26.49	100.00	17.72	0.0	3.5
14/04/2015	0.49	19.88	33.85	25.91	95.10	17.39	0.0	3.6
15/04/2015	0.54	20.98	35.09	26.01	88.30	16.92	0.0	3.7
16/04/2015	0.65	21.63	36.49	26.01	76.61	16.20	0.0	3.8
17/04/2015	0.69	20.85	36.38	0.32	73.15	17.10	0.0	3.9
18/04/2015	0.58	22.79	38.67	0.32	43.61	16.60	0.0	3.7
19/04/2015	1.29	23.61	41.55	0.32	0.39	15.74	0.0	4.8
20/04/2015	0.80	24.97	37.08	0.32	0.59	16.78	0.0	3.8
21/04/2015	0.48	20.92	38.05	0.32	0.56	18.98	0.0	3.3
22/04/2015	0.41	19.91	38.62	0.32	0.39	19.08	0.0	3.2
23/04/2015	0.60	19.89	40.16	0.32	0.39	19.70	0.0	3.6
24/04/2015	0.51	20.65	41.03	0.32	9.22	19.23	0.0	3.7
25/04/2015	0.41	22.23	41.67	0.32	14.42	18.51	0.0	3.5
26/04/2015	0.60	23.85	40.08	0.32	29.75	17.32	0.0	3.9
27/04/2015	0.96	25.21	39.63	0.32	0.39	15.34	0.0	4.2
28/04/2015	0.62	23.93	37.61	0.32	23.76	15.45	0.0	3.7

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
29/04/2015	0.46	23.62	39.35	0.32	0.39	16.13	0.0	3.2
30/04/2015	1.09	23.30	36.03	0.32	0.42	14.40	0.0	4.3
1/05/2015	0.56	19.59	36.42	0.32	0.59	16.13	0.0	3.4
2/05/2015	0.49	19.91	38.20	0.32	0.46	15.92	0.0	3.3
3/05/2015	0.55	21.44	39.32	0.32	0.53	16.06	0.0	3.4
4/05/2015	0.48	23.70	40.28	0.32	0.52	14.37	0.0	3.3
5/05/2015	0.58	20.99	42.79	0.32	46.73	16.02	0.0	3.9
6/05/2015	0.71	24.31	43.01	0.73	45.24	15.92	0.0	4.2
7/05/2015	0.95	26.01	42.15	2.25	32.53	15.77	0.0	4.6
8/05/2015	0.50	25.52	39.67	11.81	34.73	15.92	0.0	3.8
9/05/2015	0.46	26.06	40.88	7.55	52.84	14.40	0.0	3.6
10/05/2015	0.88	27.93	40.02	8.90	36.40	14.69	0.0	4.3
11/05/2015	0.71	23.40	36.25	17.25	100.00	9.83	2.1	3.0
12/05/2015	0.53	21.25	35.93	17.49	100.00	14.80	0.0	3.5
13/05/2015	0.62	23.16	33.68	26.56	84.60	9.26	0.3	2.7
14/05/2015	0.64	22.16	37.07	17.01	87.90	16.60	0.0	4.0
15/05/2015	0.69	24.67	37.91	18.97	41.77	15.84	0.0	4.0
16/05/2015	0.73	23.56	40.53	10.76	56.59	17.18	0.0	4.4
17/05/2015	0.55	25.61	43.52	6.26	45.56	16.92	0.0	4.2
18/05/2015	0.65	27.41	42.61	11.53	47.04	16.02	0.0	4.2
19/05/2015	0.74	25.16	32.17	31.39	94.90	7.31	3.3	2.4
20/05/2015	0.49	20.43	41.14	7.28	100.00	16.49	0.0	3.9
21/05/2015	0.79	23.64	42.98	1.91	77.29	17.43	0.0	4.6
22/05/2015	0.73	25.31	44.27	1.40	48.10	15.66	0.0	4.3
23/05/2015	0.68	25.77	42.83	3.36	38.15	15.52	0.0	4.2
24/05/2015	0.98	26.19	41.59	7.89	39.37	14.73	0.0	4.6
25/05/2015	0.61	26.19	41.94	7.82	47.58	13.61	0.0	3.8
26/05/2015	0.87	24.29	39.77	1.06	36.29	16.10	0.0	4.4
27/05/2015	0.56	22.72	41.73	0.39	32.92	15.34	0.0	3.8
28/05/2015	1.15	25.10	35.42	21.42	69.01	6.56	0.6	3.1
29/05/2015	0.82	24.57	37.69	14.78	77.12	14.19	3.1	3.9
30/05/2015	0.55	24.06	40.03	13.77	90.50	13.54	0.0	3.6
31/05/2015	0.93	25.21	40.30	9.04	50.34	14.66	0.0	4.4
1/06/2015	1.07	24.67	38.71	17.82	58.29	11.78	0.7	4.0
2/06/2015	0.75	22.58	36.50	16.65	55.74	14.04	0.0	3.8
3/06/2015	0.82	22.79	35.98	17.80	80.60	8.75	0.0	3.0
4/06/2015	0.54	20.97	35.04	18.24	100.00	13.18	0.0	3.3
5/06/2015	0.13	24.49	31.76	28.81	71.33	0.33	0.0	0.9
6/06/2015	0.43	24.51	39.65	12.89	80.40	13.07	0.0	3.4
7/06/2015	0.60	27.31	41.45	8.87	44.70	14.37	0.0	3.9
8/06/2015	0.46	27.48	43.26	6.91	42.54	14.58	0.0	3.8
9/06/2015	1.07	30.08	41.48	12.48	52.94	11.88	0.0	4.3

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
10/06/2015	1.30	29.31	39.77	16.43	53.99	12.71	0.0	4.6
11/06/2015	0.80	26.21	39.36	18.83	49.64	12.89	0.0	3.9
12/06/2015	0.74	28.64	41.29	14.54	67.40	14.19	0.0	4.1
13/06/2015	0.91	28.05	41.84	13.02	66.75	14.30	0.7	4.4
14/06/2015	1.63	25.22	37.60	23.03	100.00	10.34	1.4	3.9
15/06/2015	0.75	25.24	32.73	36.76	100.00	8.61	0.7	2.5
16/06/2015	0.50	24.16	34.49	45.34	100.00	9.58	0.1	2.6
17/06/2015	0.37	25.58	39.27	31.44	100.00	14.15	0.0	3.5
18/06/2015	0.34	28.01	41.20	14.64	100.00	14.87	0.0	3.7
19/06/2015	0.36	29.18	43.13	11.67	100.00	14.30	0.0	3.7
20/06/2015	0.64	29.20	43.34	14.51	83.00	13.43	0.0	3.9
21/06/2015	1.23	25.68	36.84	33.17	100.00	14.48	13.1	4.1
22/06/2015	0.42	27.85	40.30	20.45	100.00	14.08	0.0	3.6
23/06/2015	0.98	28.28	33.15	44.35	100.00	10.08	0.5	2.9
24/06/2015	0.81	23.40	30.22	99.90	100.00	8.10	1.0	1.8
25/06/2015	0.48	23.20	35.01	27.77	100.00	16.20	0.0	3.7
26/06/2015	0.47	25.70	37.04	31.07	100.00	14.22	0.0	3.5
27/06/2015	0.64	27.50	39.46	26.13	100.00	14.36	0.0	3.8
28/06/2015	0.85	29.60	41.04	16.94	99.90	14.65	0.0	4.2
29/06/2015	0.77	28.20	40.99	19.54	99.90	14.58	0.0	4.1
30/06/2015	0.87	28.00	38.10	18.97	100.00	13.00	0.0	3.8
1/07/2015	0.80	28.20	39.36	20.39	100.00	14.80	0.0	4.1
2/07/2015	0.73	26.60	35.96	30.13	100.00	14.47	0.0	3.7
3/07/2015	0.74	28.10	38.16	29.41	100.00	13.21	0.0	3.6
4/07/2015	0.98	29.10	39.68	22.75	100.00	14.26	0.0	4.2
5/07/2015	1.11	30.00	39.01	26.47	83.40	13.79	0.7	4.2
6/07/2015	0.97	30.80	38.33	30.93	81.00	13.28	0.0	3.9
7/07/2015	0.93	22.90	31.99	49.88	100.00	4.50	28.9	1.8
8/07/2015	0.43	25.40	34.17	58.09	100.00	12.49	0.0	3.0
9/07/2015	0.66	27.80	36.35	42.16	100.00	13.18	0.0	3.4
10/07/2015	0.75	27.00	35.15	48.07	100.00	13.03	0.0	3.3
11/07/2015	0.92	22.50	31.96	61.62	100.00	11.84	13.8	2.9
12/07/2015	0.46	24.00	32.22	62.83	100.00	13.43	0.0	3.1
13/07/2015	0.40	26.50	35.01	47.37	100.00	14.44	0.0	3.4
14/07/2015	0.62	28.50	37.36	39.79	100.00	15.08	0.0	3.8
15/07/2015	0.77	29.80	37.54	33.98	99.90	14.51	0.0	3.9
16/07/2015	0.89	29.50	37.67	33.60	76.13	14.44	0.0	4.0
17/07/2015	0.67	31.40	37.30	35.29	58.22	12.20	0.0	3.5
18/07/2015	0.25	29.40	29.41	99.90	99.90	0.22	0.0	0.3
19/07/2015	0.75	29.10	36.67	37.42	100.00	10.62	0.0	3.0
20/07/2015	0.86	28.70	36.28	43.61	75.69	10.62	0.0	3.2
21/07/2015	0.96	30.10	36.60	37.02	91.10	10.98	0.0	3.3

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
22/07/2015	0.73	28.50	36.77	34.82	99.90	11.12	0.1	3.1
23/07/2015	0.72	26.60	37.57	37.84	100.00	11.34	13.0	3.2
24/07/2015	0.44	25.50	34.96	51.18	100.00	13.03	0.6	3.1
25/07/2015	0.28	24.80	29.39	99.90	100.00	0.47	0.1	0.4
26/07/2015	0.96	25.60	33.90	61.22	100.00	11.63	0.2	3.0
27/07/2015	1.89	26.80	31.83	63.04	100.00	9.65	0.9	2.8
28/07/2015	1.06	25.50	31.30	56.38	100.00	7.70	3.8	2.3
29/07/2015	1.38	25.70	30.41	66.31	100.00	6.70	0.2	2.0
30/07/2015	1.06	25.60	31.13	65.07	100.00	5.72	1.7	1.8
31/07/2015	1.00	25.40	30.50	56.61	100.00	7.81	14.8	2.2
1/08/2015	0.85	22.70	28.43	0.34	100.00	3.20	101.2	2.0
2/08/2015	0.58	24.70	29.07	99.90	100.00	6.84	2.9	1.6
3/08/2015	0.48	26.20	32.48	0.34	100.00	11.70	0.0	3.0
4/08/2015	0.48	28.10	33.31	0.34	100.00	9.83	0.0	2.7
5/08/2015	0.31	27.00	35.39	0.34	100.00	15.95	0.0	3.5
6/08/2015	0.44	29.10	36.38	0.34	100.00	16.42	0.0	3.8
7/08/2015	0.52	28.70	36.15	0.34	58.15	15.37	0.0	3.7
8/08/2015	0.56	28.70	35.80	0.34	99.90	15.41	0.0	3.8
9/08/2015	0.54	28.30	36.03	0.34	100.00	15.48	0.0	3.8
10/08/2015	0.56	28.60	36.08	0.34	15.63	14.40	0.0	3.5
11/08/2015	0.10	28.90	30.47	0.34	100.00	0.22	0.0	0.8
12/08/2015	0.69	29.10	34.79	0.34	100.00	12.24	0.0	3.4
13/08/2015	0.52	27.70	35.64	0.34	100.00	12.17	0.0	3.2
14/08/2015	0.36	26.80	31.08	0.34	100.00	0.18	0.0	1.1
15/08/2015	0.35	25.20	30.22	17.33	100.00	0.36	0.9	1.0
16/08/2015	0.47	24.60	34.05	0.34	100.00	17.35	0.0	3.7
17/08/2015	0.51	27.70	36.11	0.34	100.00	16.56	0.0	3.8
18/08/2015	0.61	28.30	36.19	0.34	100.00	16.85	0.0	4.0
19/08/2015	0.88	28.20	35.74	0.34	100.00	15.66	0.0	4.1
20/08/2015	0.84	27.60	34.67	51.11	72.53	15.05	0.0	3.8
21/08/2015	0.73	27.20	33.97	56.31	81.60	14.15	0.0	3.4
22/08/2015	0.70	27.60	34.67	55.03	82.40	14.11	0.0	3.5
23/08/2015	0.82	24.00	34.81	50.80	86.50	14.26	0.0	3.5
24/08/2015	0.66	23.60	35.73	47.69	92.30	15.16	0.0	3.6
25/08/2015	0.55	27.60	35.96	51.23	88.80	12.24	0.0	3.1
26/08/2015	0.60	27.50	36.31	48.70	77.62	12.74	0.0	3.2
27/08/2015	0.66	28.00	36.25	49.09	77.16	12.89	0.0	3.3
28/08/2015	0.59	27.50	35.65	49.75	89.30	11.84	0.0	3.0
29/08/2015	0.49	27.20	36.72	43.56	92.70	12.31	0.0	3.1
30/08/2015	0.68	27.90	36.75	41.30	72.83	11.81	0.0	3.2
31/08/2015	0.71	27.30	36.06	42.41	79.23	12.24	0.0	3.2
1/09/2015	0.52	27.30	35.90	44.04	90.80	11.05	0.0	2.8

Date	Wind speed @10m (m/s)	T_{min} (˚C)	T_{max} (˚C)	RH $_{min}$ (%)	RH $_{max}$ (%)	R_s (MJ/ m^2/d)	Rainfall (mm)	ET_{os} (mm/d)
2/09/2015	0.73	26.40	36.23	35.62	69.47	12.53	0.0	3.3
3/09/2015	0.70	25.30	36.22	32.28	74.17	13.46	0.0	3.4
4/09/2015	0.52	24.03	37.34	32.37	86.50	13.50	0.0	3.3
5/09/2015	0.66	25.14	37.32	31.83	86.50	13.50	0.0	3.4
6/09/2015	0.57	25.17	37.03	29.71	82.80	11.74	0.0	3.0
7/09/2015	0.52	25.28	37.19	33.01	78.76	13.64	0.0	3.3
8/09/2015	0.47	23.43	37.33	29.67	84.60	13.18	0.0	3.1
9/09/2015	0.49	23.43	38.32	24.33	83.00	13.07	0.0	3.2
10/09/2015	0.41	24.55	38.23	29.70	88.30	12.13	0.0	3.0
11/09/2015	0.53	24.62	39.03	26.69	87.30	10.76	0.0	2.9
12/09/2015	0.47	24.62	39.20	26.22	87.50	10.40	0.0	2.8
13/09/2015	0.36	23.61	38.18	29.67	81.70	10.51	0.0	2.6
14/09/2015	0.52	24.78	38.94	26.86	88.30	8.46	0.0	2.5
15/09/2015	0.49	23.20	38.86	34.73	84.30	10.51	0.0	2.8
16/09/2015	0.40	23.94	38.83	29.49	84.60	9.58	0.0	2.5
17/09/2015	0.40	24.73	37.90	34.53	88.90	9.50	0.0	2.5
18/09/2015	0.50	23.87	36.87	37.07	85.50	8.75	0.0	2.4
19/09/2015	0.56	24.81	33.31	53.62	87.20	8.21	0.0	2.2
20/09/2015	0.96	24.27	29.73	63.60	90.70	6.95	0.0	2.0
21/09/2015	0.96	23.77	30.33	69.22	97.80	5.80	46.0	1.7
22/09/2015	0.92	22.87	26.92	84.80	97.70	6.95	25.4	1.6
23/09/2015	0.54	23.00	32.95	52.15	99.20	2.99	38.9	1.3
24/09/2015	0.50	22.91	32.88	46.32	95.30	8.06	0.0	2.1
25/09/2015	0.21	22.51	25.51	63.60	87.80	8.24	0.0	1.8
26/09/2015	0.35	22.71	29.20	54.96	86.20	0.22	0.0	0.8
27/09/2015	0.32	27.71	28.40	70.95	71.62	0.20	0.0	0.7
28/09/2015	0.30	29.61	29.61	66.76	66.76	0.07	0.0	0.7
29/09/2015	0.33	25.80	27.19	75.14	76.47	0.32	0.0	0.7
30/09/2015	0.41	22.05	33.81	44.56	95.70	7.78	0.0	2.0
1/10/2015	0.35	22.32	35.65	30.22	99.20	8.17	0.1	2.1
2/10/2015	0.39	23.04	36.37	25.89	84.60	7.99	0.0	2.2
3/10/2015	0.39	21.84	37.51	23.22	85.70	7.85	0.0	2.2
4/10/2015	0.36	22.69	36.79	26.80	87.00	7.16	0.0	2.0
5/10/2015	0.42	21.59	34.55	43.17	93.80	6.66	0.0	1.8
6/10/2015	0.30	22.75	35.85	30.28	97.90	7.56	0.0	1.9
7/10/2015	0.43	22.94	36.88	24.33	89.90	7.63	0.0	2.1
8/10/2015	0.33	21.51	37.20	20.85	96.40	8.14	0.0	2.1
9/10/2015	0.60	21.11	37.43	20.41	86.40	8.10	0.0	2.4

APPENDIX B - GROUNDWATER DATA

Date	Average depth (m)	Average Specific conductivity (dS/m)
13/06/2014	1.73	5.21
14/06/2014	1.74	5.23
15/06/2014	1.78	5.22
16/06/2014	1.74	5.35
17/06/2014	1.78	5.49
18/06/2014	1.76	5.68
19/06/2014	1.82	6.10
20/06/2014	1.81	6.10
21/06/2014	1.80	5.87
22/06/2014	1.83	5.72
23/06/2014	1.81	5.60
24/06/2014	1.82	5.57
25/06/2014	1.82	5.46
26/06/2014	1.79	5.38
27/06/2014	1.81	5.39
28/06/2014	1.81	5.37
29/06/2014	1.79	5.29
30/06/2014	1.79	5.17
01/07/2014	1.79	5.23
02/07/2014	1.77	5.29
03/07/2014	1.76	5.31
04/07/2014	1.77	5.20
05/07/2014	1.76	5.09
06/07/2014	1.76	5.03
07/07/2014	1.53	5.11
08/07/2014	1.61	5.17
09/07/2014	2.11	5.13
10/07/2014	2.15	5.07
11/07/2014	2.53	6.20
12/07/2014	1.94	7.08
13/07/2014	2.15	6.95
14/07/2014	2.14	6.73
15/07/2014	2.14	6.57
16/07/2014	2.15	6.47
17/07/2014	2.16	6.48
18/07/2014	2.17	6.46
19/07/2014	2.20	6.42
20/07/2014	2.21	6.40
21/07/2014	2.23	6.36
22/07/2014	2.27	6.29
23/07/2014	2.30	6.23
24/07/2014	2.30	6.20

Date	Average depth (m)	Average Specific conductivity (dS/m)
25/07/2014	2.29	6.18
26/07/2014	2.27	6.16
27/07/2014	2.32	6.14
28/07/2014	2.31	6.19
29/07/2014	2.28	6.26
30/07/2014	2.27	6.36
31/07/2014	2.27	6.47
01/08/2014	2.27	6.51
02/08/2014	2.28	6.51
03/08/2014	2.29	6.54
04/08/2014	2.27	6.60
05/08/2014	2.26	6.41
06/08/2014	2.27	6.32
07/08/2014	2.30	6.27
08/08/2014	2.30	6.18
09/08/2014	2.31	6.19
10/08/2014	2.32	6.25
11/08/2014	2.37	6.19
12/08/2014	2.44	6.16
13/08/2014	2.46	6.11
14/08/2014	2.51	6.06
15/08/2014	2.56	5.99
16/08/2014	2.52	6.04
17/08/2014	2.51	6.08
18/08/2014	2.50	6.20
19/08/2014	2.50	6.33
20/08/2014	2.54	6.45
21/08/2014	2.58	6.45
22/08/2014	2.57	6.46
23/08/2014	2.58	6.45
24/08/2014	2.62	6.38
25/08/2014	2.61	6.45
26/08/2014	2.61	6.35
27/08/2014	2.64	6.28
28/08/2014	2.63	6.18
29/08/2014	2.56	6.20
30/08/2014	2.57	6.18
31/08/2014	2.58	6.14
01/09/2014	2.33	6.10
02/09/2014	2.32	6.05
03/09/2014	2.32	6.07
04/09/2014	2.31	6.11
05/09/2014	2.23	6.17
06/09/2014	2.16	6.29

Date	Average depth (m)	Average Specific conductivity (dS/m)
07/09/2014	2.12	6.37
08/09/2014	2.09	6.41
09/09/2014	2.08	6.42
10/09/2014	2.08	6.40
11/09/2014	2.08	6.41
12/09/2014	2.07	6.46
13/09/2014	2.05	6.51
14/09/2014	2.06	6.43
15/09/2014	2.04	6.28
16/09/2014	2.03	6.28
17/09/2014	2.04	6.32
18/09/2014	2.07	6.44
19/09/2014	2.08	6.49
20/09/2014	2.07	6.54
21/09/2014	2.15	6.49
22/09/2014	2.14	6.48
23/09/2014	2.14	6.80
24/09/2014	2.15	6.78
25/09/2014	2.16	6.99
26/09/2014	2.17	6.96
27/09/2014	2.18	6.89
28/09/2014	2.21	6.88
29/09/2014	2.22	6.84
30/09/2014	2.23	6.99
01/10/2014	2.25	6.99
02/10/2014	2.26	6.99
03/10/2014	2.28	6.89
04/10/2014	2.29	6.87
05/10/2014	2.35	7.02
06/10/2014	2.32	6.90
07/10/2014	2.31	6.87
08/10/2014	2.33	7.01
09/10/2014	2.33	7.30
10/10/2014	2.32	7.50
11/10/2014	2.32	7.42
12/10/2014	2.32	7.34
13/10/2014	2.31	7.25
14/10/2014	2.31	7.29
15/10/2014	2.31	7.25
16/10/2014	2.30	7.29
17/10/2014	2.30	7.37
18/10/2014	2.30	7.34
19/10/2014	2.30	7.32
20/10/2014	2.28	7.28

Date	Average depth (m)	Average Specific conductivity (dS/m)
21/10/2014	2.27	7.18
22/10/2014	2.27	7.09
23/10/2014	2.27	7.38
24/10/2014	2.27	7.50
25/10/2014	2.28	7.45
26/10/2014	2.29	7.43
27/10/2014	2.28	7.40
28/10/2014	2.29	7.39
29/10/2014	2.30	7.35
30/10/2014	2.59	7.03
31/10/2014	2.34	7.18
01/11/2014	2.31	7.09
02/11/2014	2.32	6.98
03/11/2014	2.31	6.98
04/11/2014	2.29	6.84
05/11/2014	2.29	6.73
06/11/2014	2.29	6.76
07/11/2014	2.27	6.75
08/11/2014	2.25	6.72
09/11/2014	2.27	6.69
10/11/2014	2.25	6.65
11/11/2014	2.21	6.61
12/11/2014	2.20	6.62
13/11/2014	2.20	6.64
14/11/2014	2.19	6.64
15/11/2014	2.17	6.64
16/11/2014	2.17	6.65
17/11/2014	2.18	6.87
18/11/2014	2.19	6.86
19/11/2014	2.18	6.85
20/11/2014	2.24	6.83
21/11/2014	2.22	6.89
22/11/2014	2.20	6.92
23/11/2014	2.22	6.82
24/11/2014	2.18	6.80
25/11/2014	2.17	6.79
26/11/2014	2.15	6.80
27/11/2014	2.15	6.81
28/11/2014	2.14	6.85
29/11/2014	2.12	6.89
30/11/2014	2.11	6.91
01/12/2014	2.08	6.93
02/12/2014	2.06	6.93
03/12/2014	2.06	6.93

Date	Average depth (m)	Average Specific conductivity (dS/m)
04/12/2014	2.06	6.94
05/12/2014	2.04	6.97
06/12/2014	2.03	6.97
07/12/2014	2.03	6.91
08/12/2014	2.00	6.94
09/12/2014	2.00	7.02
10/12/2014	1.97	7.09
11/12/2014	1.97	7.13
12/12/2014	1.98	7.06
13/12/2014	1.98	7.18
14/12/2014	1.99	7.17
15/12/2014	1.94	7.15
16/12/2014	1.95	7.16
17/12/2014	1.94	7.12
18/12/2014	1.95	7.08
19/12/2014	1.94	7.08
20/12/2014	1.93	7.10
21/12/2014	1.92	7.14
22/12/2014	1.88	7.15
23/12/2014	1.88	7.17
24/12/2014	1.89	7.15
25/12/2014	1.88	7.13
26/12/2014	1.86	7.15
27/12/2014	1.81	7.21
28/12/2014	1.80	7.11
29/12/2014	1.81	7.17
30/12/2014	1.81	7.21
31/12/2014	1.87	7.18
01/01/2015	1.92	7.20
02/01/2015	1.88	7.21
03/01/2015	1.83	7.26
04/01/2015	1.84	7.11
05/01/2015	1.82	7.23
06/01/2015	1.83	7.38
07/01/2015	1.82	7.30
08/01/2015	1.83	7.24
09/01/2015	1.84	7.21
10/01/2015	1.86	7.14
11/01/2015	1.86	7.21
12/01/2015	1.85	7.23
13/01/2015	1.85	7.22
14/01/2015	1.86	7.20
15/01/2015	1.86	7.21
16/01/2015	1.86	7.27

Date	Average depth (m)	Average Specific conductivity (dS/m)
17/01/2015	1.86	7.27
18/01/2015	1.88	7.29
19/01/2015	1.91	7.31
20/01/2015	1.92	7.32
21/01/2015	1.90	7.34
22/01/2015	1.87	7.40
23/01/2015	1.90	7.40
24/01/2015	1.91	7.35
25/01/2015	1.93	7.31
26/01/2015	1.91	7.28
27/01/2015	1.90	7.25
28/01/2015	1.91	7.23
29/01/2015	1.92	7.21
30/01/2015	1.92	7.21
31/01/2015	1.93	7.23
01/02/2015	1.93	7.22
02/02/2015	1.94	7.20
03/02/2015	1.92	7.17
04/02/2015	1.91	7.22
05/02/2015	1.91	7.25
06/02/2015	1.92	7.24
07/02/2015	1.93	7.15
08/02/2015	1.92	7.06
09/02/2015	1.76	7.14
10/02/2015	1.93	7.25
11/02/2015	1.91	7.30
12/02/2015	1.94	7.31
13/02/2015	1.94	7.37
14/02/2015	1.90	7.28
15/02/2015	1.95	7.26
16/02/2015	1.94	7.53
17/02/2015	1.94	7.58
18/02/2015	1.94	7.59
19/02/2015	1.94	7.55
20/02/2015	1.94	7.53
21/02/2015	1.94	7.51
22/02/2015	1.93	7.54
23/02/2015	1.94	7.55
24/02/2015	1.91	7.55
25/02/2015	1.74	7.53
26/02/2015	1.82	7.50
27/02/2015	1.87	7.44
28/02/2015	1.91	7.53
01/03/2015	1.78	7.53

Date	Average depth (m)	Average Specific conductivity (dS/m)
02/03/2015	1.66	7.52
03/03/2015	1.62	7.52
04/03/2015	1.68	7.49
05/03/2015	1.64	7.46
06/03/2015	1.65	7.40
07/03/2015	1.65	7.42
08/03/2015	1.65	7.43
09/03/2015	1.65	7.43
10/03/2015	1.64	7.44
11/03/2015	1.63	7.42
12/03/2015	1.64	7.40
13/03/2015	1.66	7.40
14/03/2015	1.66	7.38
15/03/2015	1.66	7.37
16/03/2015	1.45	7.46
17/03/2015	1.24	7.57
18/03/2015	1.63	7.69
19/03/2015	1.71	7.73
20/03/2015	1.75	7.70
21/03/2015	1.77	7.67
22/03/2015	1.77	7.65
23/03/2015	1.76	7.63
24/03/2015	1.77	7.63
25/03/2015	1.77	7.65
26/03/2015	1.78	7.68
27/03/2015	1.80	7.69
28/03/2015	1.76	7.71
29/03/2015	1.73	7.74
30/03/2015	1.72	7.79
31/03/2015	1.73	7.83
01/04/2015	1.99	7.81
02/04/2015	1.73	7.78
03/04/2015	1.62	7.73
04/04/2015	1.73	7.70
05/04/2015	1.71	7.68
06/04/2015	1.72	7.67
07/04/2015	1.72	7.61
08/04/2015	1.72	7.57
09/04/2015	1.72	7.54
10/04/2015	1.69	7.52
11/04/2015	1.64	7.54
12/04/2015	1.61	7.52
13/04/2015	1.61	7.48
14/04/2015	1.61	7.45

Date	Average depth (m)	Average Specific conductivity (dS/m)
15/04/2015	1.62	7.40
16/04/2015	1.63	7.38
17/04/2015	1.61	7.37
18/04/2015	1.58	7.38
19/04/2015	1.58	7.41
20/04/2015	1.54	7.45
21/04/2015	1.57	7.50
22/04/2015	1.58	7.51
23/04/2015	1.60	7.52
24/04/2015	1.60	7.53
25/04/2015	1.58	7.51
26/04/2015	1.58	7.52
27/04/2015	1.56	7.50
28/04/2015	1.59	7.45
29/04/2015	1.60	7.41
30/04/2015	1.62	7.42
01/05/2015	1.64	7.45
02/05/2015	1.58	7.46
03/05/2015	1.59	7.54
04/05/2015	1.57	7.63
05/05/2015	1.55	7.67
06/05/2015	1.56	7.70
07/05/2015	1.59	7.71
08/05/2015	1.60	7.73
09/05/2015	1.57	7.71
10/05/2015	1.58	7.67
11/05/2015	1.50	7.63
12/05/2015	1.55	7.59
13/05/2015	1.57	7.58
14/05/2015	1.61	7.58
15/05/2015	1.59	7.57
16/05/2015	1.55	7.56
17/05/2015	1.55	7.64
18/05/2015	1.51	7.59
19/05/2015	1.48	7.55
20/05/2015	1.56	7.54
21/05/2015	1.49	7.56
22/05/2015	1.51	7.54
23/05/2015	1.49	7.51
24/05/2015	1.51	7.49
25/05/2015	1.52	7.43
26/05/2015	1.56	7.42
27/05/2015	1.69	7.35
28/05/2015	1.60	7.27

Date	Average depth (m)	Average Specific conductivity (dS/m)
29/05/2015	1.64	7.22
30/05/2015	1.68	7.18
31/05/2015	1.63	7.12
01/06/2015	1.58	7.07
02/06/2015	1.65	7.01
03/06/2015	1.64	6.95
04/06/2015	1.69	6.90
05/06/2015	1.55	6.83
06/06/2015	1.62	6.75
07/06/2015	1.58	7.16
08/06/2015	1.52	7.39
09/06/2015	1.57	7.34
10/06/2015	1.63	7.17
11/06/2015	1.69	7.04
12/06/2015	1.63	6.92
13/06/2015	1.57	6.84
14/06/2015	1.51	6.86
15/06/2015	1.53	6.91
16/06/2015	0.19	6.90
17/06/2015	1.56	6.88
18/06/2015	1.58	6.86
19/06/2015	1.59	6.84
20/06/2015	1.60	6.81
21/06/2015	1.46	6.75
22/06/2015	1.61	6.80
23/06/2015	1.58	6.78
24/06/2015	0.51	6.74
25/06/2015	1.55	6.70
26/06/2015	1.64	7.00
27/06/2015	1.61	7.29
28/06/2015	1.63	7.37
29/06/2015	1.61	7.35
30/06/2015	1.60	7.30
01/07/2015	1.63	7.25
02/07/2015	1.65	7.22
03/07/2015	1.68	7.18
04/07/2015	1.65	7.17
05/07/2015	1.67	7.33
06/07/2015	1.64	7.31
07/07/2015	1.41	7.23
08/07/2015	0.73	7.32
09/07/2015	1.50	7.32
10/07/2015	1.52	7.22
11/07/2015	0.99	7.05

Date	Average depth (m)	Average Specific conductivity (dS/m)
12/07/2015	1.30	7.21
13/07/2015	1.31	7.23
14/07/2015	1.34	7.17
15/07/2015	1.36	7.07
16/07/2015	1.40	6.99
17/07/2015	1.53	6.93
18/07/2015	1.39	6.85
19/07/2015	0.56	6.75
20/07/2015	1.47	6.92
21/07/2015	1.56	6.91
22/07/2015	1.47	6.85
23/07/2015	1.24	6.78
24/07/2015	-0.24	6.82
25/07/2015	0.62	6.81
26/07/2015	-0.40	6.86
27/07/2015	1.19	6.93
28/07/2015	-0.60	6.90
29/07/2015	-1.14	6.87
30/07/2015	1.29	6.82
31/07/2015	-1.40	6.81
01/08/2015	-1.56	6.86
02/08/2015	0.56	6.91
03/08/2015	0.62	6.91
04/08/2015	0.62	6.94
05/08/2015	0.64	6.94
06/08/2015	0.67	6.88
07/08/2015	0.74	6.79
08/08/2015	0.81	6.91
09/08/2015	0.87	6.80
10/08/2015	0.93	6.57
11/08/2015	0.99	6.74
12/08/2015	0.98	7.23
13/08/2015	1.01	7.38
14/08/2015	1.01	7.66
15/08/2015	1.04	7.77
16/08/2015	1.07	7.83
17/08/2015	1.01	7.90
18/08/2015	1.19	7.92
19/08/2015	1.24	7.96
20/08/2015	1.28	8.05
21/08/2015	1.30	8.10
22/08/2015	1.29	8.15
23/08/2015	1.31	8.22
24/08/2015	1.30	8.20

Date	Average depth (m)	Average Specific conductivity (dS/m)
25/08/2015	1.32	8.12
26/08/2015	1.32	8.05
27/08/2015	1.36	8.04
28/08/2015	1.45	8.20
29/08/2015	1.50	8.16
30/08/2015	1.49	8.11
31/08/2015	1.65	8.05
01/09/2015	1.62	8.01
02/09/2015	1.66	7.97
03/09/2015	1.59	7.92
04/09/2015	1.54	7.86
05/09/2015	1.64	7.84
06/09/2015	1.65	7.89
07/09/2015	1.50	7.98
08/09/2015	1.45	7.98
09/09/2015	1.50	7.92
10/09/2015	1.49	7.84
11/09/2015	1.65	7.79
12/09/2015	1.52	7.87
13/09/2015	1.67	8.05
14/09/2015	1.60	8.09
15/09/2015	1.63	8.04
16/09/2015	1.68	7.94
17/09/2015	1.75	7.91
18/09/2015	1.68	7.88
19/09/2015	1.65	7.93
20/09/2015	1.59	7.96
21/09/2015	1.35	8.50
22/09/2015	2.14	8.17
23/09/2015	2.14	7.67
24/09/2015	2.15	7.67
25/09/2015	2.16	7.67
26/09/2015	2.17	7.64
27/09/2015	2.18	8.03
28/09/2015	2.21	7.95
29/09/2015	2.22	7.92
30/09/2015	2.23	7.90
01/10/2015	2.25	7.91
02/10/2015	2.26	7.86
03/10/2015	2.28	7.94
04/10/2015	2.29	8.06
05/10/2015	2.35	7.02
06/10/2015	2.32	6.90
07/10/2015	2.31	6.87

Date	Average depth (m)	Average Specific conductivity (dS/m)
08/10/2015	2.33	7.01
09/10/2015	2.33	7.30

APPENDIX C - IRRIGATION SCHEDULES

C.1.Kharif 2014 Schedules

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
									PID								
1	12	9	0	8	15	3	12	14	15	17	16	18	19	12	1	3	16
2	1	10	12	10	20	16	21	1	16	17	17	19	19	14	15	1	6
3	14	11	21	10	20	16	22	16	17	2	17	17	15	14	17	11	9
4	4	2	8	3	8	1	8	3	4	14	8	6	15	3	4	13	9
5	9	10	10	8	14	13	22	3	11	18	14	12	20	11	10	12	6
6	15	14	3	11	18	18	22	15	15	14	15	18	11	21	14	10	13
7	14	14	2	12	11	12	16	17	16	14	15	12	7	22	12	8	17
8	11	10	1	8	14	5	7	13	15	15	9	4	18	20	3	9	16
9	2	9	9	8	17	16	25	2	14	12	17	18	9	14	12	1	2
10	16	15	18	12	21	20	29	17	17	0	19	19	1	20	15	9	18
11	15	13	3	11	7	3	5	16	2	18	6	3	19	19	3	9	18
12	3	15	2	12	14	17	26	4	13	19	17	15	22	21	14	3	8
13	11	15	4	12	21	20	24	12	16	7	19	19	9	20	13	2	12
14	16	15	6	11	15	8	14	18	9	11	12	11	11	22	5	5	13
15	10	17	7	13	10	8	9	12	6	20	9	8	22	24	4	4	9
16	5	16	24	13	26	21	30	6	17	15	20	20	17	17	10	1	8
17	16	17	22	13	23	18	26	19	16	2	19	19	2	21	9	5	20
18	15	17	5	13	1	1	2	20	1	20	3	1	22	21	1	6	15
19	1	18	23	13	26	20	35	1	17	19	18	19	20	26	10	2	7
20	14	18	24	13	28	18	36	16	17	4	20	20	5	24	10	13	17
21	15	16	10	13	16	10	20	19	9	12	11	10	13	18	6	17	19
22	5	7	12	6	14	10	13	5	9	18	10	10	19	5	5	3	7
23	10	18	21	13	30	18	27	7	17	13	18	18	14	15	10	5	4
24	16	18	19	13	25	14	26	18	14	5	16	16	5	24	8	14	10
25	14	12	3	9	5	2	3	17	2	21	3	3	21	18	2	14	7

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
26	0	17	24	14	36	19	36	0	17	18	20	16	23	23	10	1	6
								SCENARIO A									
1	15.0	12.0	13.0	13.0	18.0	12.0	16.0	16.0	11.0	13.0	15.0	12.0	13.0	12.0	14.0	12.0	12.0
2	0.0	2.0	2.0	2.0	2.0	18.0	2.0	19.0	0.0	20.0	17.0	2.0	13.0	2.0	16.0	2.0	0.0
3	15.0	12.0	13.0	13.0	18.0	18.0	16.0	19.0	11.0	1.0	19.0	12.0	0.0	12.0	11.0	12.0	15.0
4	2.0	0.0	17.0	2.0	21.0	1.0	0.0	0.0	1.0	16.0	0.0	1.0	13.0	0.0	14.0	15.0	12.0
5	15.0	12.0	1.0	13.0	2.0	15.0	16.0	16.0	11.0	12.0	15.0	12.0	0.0	12.0	0.0	0.0	15.0
6	0.0	2.0	13.0	2.0	18.0	18.0	2.0	0.0	11.0	16.0	19.0	2.0	13.0	2.0	14.0	12.0	18.0
7	15.0	12.0	13.0	13.0	18.0	2.0	16.0	16.0	11.0	20.0	19.0	12.0	1.0	12.0	16.0	12.0	18.0
8	0.0	2.0	2.0	2.0	2.0	15.0	2.0	19.0	0.0	13.0	0.0	0.0	13.0	2.0	16.0	0.0	18.0
9	15.0	12.0	13.0	13.0	18.0	18.0	16.0	0.0	11.0	0.0	15.0	12.0	0.0	12.0	14.0	12.0	15.0
10	2.0	0.0	2.0	0.0	21.0	18.0	0.0	16.0	0.0	16.0	2.0	1.0	13.0	0.0	0.0	0.0	18.0
11	15.0	12.0	13.0	13.0	21.0	2.0	16.0	20.0	11.0	16.0	15.0	12.0	2.0	12.0	14.0	12.0	18.0
12	0.0	2.0	2.0	2.0	2.0	15.0	2.0	19.0	2.0	20.0	0.0	0.0	13.0	2.0	16.0	2.0	18.0
13	15.0	12.0	13.0	13.0	18.0	18.0	16.0	20.0	11.0	6.0	15.0	12.0	2.0	12.0	2.0	12.0	18.0
14	0.0	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	16.0	0.0	0.0	13.0	0.0	14.0	0.0	18.0
15	15.0	12.0	13.0	13.0	18.0	18.0	16.0	16.0	11.0	20.0	15.0	12.0	10.0	12.0	2.0	12.0	1.0
16	0.0	2.0	2.0	10.0	0.0	18.0	13.0	20.0	11.0	20.0	2.0	12.0	13.0	0.0	14.0	9.0	15.0
17	15.0	12.0	13.0	13.0	18.0	18.0	16.0	2.0	13.0	16.0	15.0	1.0	1.0	12.0	2.0	12.0	18.0
18	0.0	2.0	2.0	2.0	2.0	18.0	2.0	16.0	0.0	14.0	0.0	12.0	13.0	2.0	14.0	2.0	18.0
19	15.0	12.0	13.0	13.0	18.0	18.0	16.0	19.0	11.0	13.0	15.0	0.0	0.0	12.0	0.0	12.0	18.0
20	0.0	2.0	2.0	2.0	2.0	18.0	2.0	16.0	2.0	16.0	2.0	12.0	13.0	2.0	14.0	1.0	18.0
21	15.0	12.0	13.0	13.0	18.0	18.0	16.0	19.0	11.0	13.0	15.0	1.0	0.0	12.0	0.0	12.0	18.0
22	2.0	15.0	15.0	14.0	19.0	2.0	16.0	2.0	13.0	16.0	2.0	12.0	13.0	2.0	14.0	15.0	18.0
23	15.0	2.0	2.0	0.0	2.0	15.0	2.0	16.0	0.0	13.0	15.0	0.0	0.0	12.0	0.0	0.0	18.0
24	0.0	12.0	13.0	13.0	18.0	0.0	16.0	0.0	11.0	16.0	19.0	12.0	13.0	2.0	14.0	12.0	13.0
25	15.0	9.0	15.0	2.0	4.0	15.0	2.0	16.0	2.0	13.0	0.0	0.0	0.0	12.0	16.0	1.0	16.0
26	0.0	12.0	11.0	13.0	18.0	18.0	16.0	1.0	11.0	16.0	15.0	12.0	13.0	2.0	0.0	12.0	18.0

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
								SCENARIO I									
1	15	12	13	13	18	12	16	16	11	13	15	12	13	12	14	12	12
2	0	12	13	13	0	14	16	13	11	16	0	12	13	12	14	12	15
3	15	12	13	13	18	15	0	16	11	1	15	12	13	12	14	12	14
4	15	12	13	13	18	0	16	0	11	16	15	12	12	12	14	12	0
5	15	12	13	13	18	15	16	16	11	0	18	12	13	12	17	12	15
6	15	12	13	13	18	15	16	16	11	16	13	12	13	12	0	12	15
7	15	12	13	13	0	12	16	14	11	16	15	12	13	12	14	12	12
8	15	12	13	13	18	15	0	13	11	13	0	12	12	12	14	12	15
9	0	12	0	13	18	14	16	0	11	16	15	12	11	12	14	12	0
10	15	12	13	13	23	0	16	16	11	17	15	12	13	12	14	12	15
11	15	12	13	13	0	15	16	15	11	13	13	12	11	12	14	12	12
12	15	12	13	13	18	14	0	13	11	16	12	12	11	12	14	12	15
13	15	12	13	13	0	15	16	0	11	13	15	12	13	12	14	12	15
14	15	12	13	13	18	15	16	16	11	0	15	12	13	12	14	12	15
15	15	12	13	13	0	15	16	16	11	16	0	12	13	12	0	12	13
16	15	12	13	13	18	15	0	16	11	13	15	12	13	12	14	12	14
17	0	12	13	12	18	12	16	16	11	13	15	12	13	12	14	12	15
18	15	12	13	13	0	0	16	16	11	16	15	12	13	12	14	12	15
19	15	12	13	13	18	15	0	13	11	13	15	12	13	12	14	12	15
20	15	12	13	13	18	15	16	16	11	16	2	12	13	12	14	12	15
21	15	12	13	13	18	15	16	16	11	10	15	12	13	12	14	12	15
22	15	12	13	13	18	15	16	3	11	16	15	12	13	12	14	12	0
23	15	12	13	13	23	17	16	16	11	0	15	12	16	12	14	12	15
24	15	12	13	13	0	12	16	16	11	16	13	12	12	12	14	12	0
25	0	12	13	13	18	15	16	14	11	0	15	12	13	12	14	12	15
26	15	12	13	13	23	15	16	0	11	16	18	12	13	12	14	12	15

*Units in mm

C.2.Rabi 2014/2015 Schedules

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
								PID									
1	3.0	3.0	4.0	2.0	5.0	3.0	5.0	3.0	3.0	1.0	3.0	5.0	1.0	3.0	2.0	2.0	3.0
2	3.0	1.0	2.0	2.0	2.0	1.0	2.0	3.0	2.0	2.0	2.0	20.0	3.0	2.0	1.0	2.0	3.0
3	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	2.0	3.0	2.0	14.0	2.0	2.0	1.0	1.0	2.0
4	2.0	2.0	4.0	3.0	5.0	3.0	6.0	2.0	3.0	2.0	3.0	14.0	2.0	3.0	1.0	1.0	2.0
5	3.0	2.0	3.0	2.0	4.0	3.0	3.0	3.0	2.0	2.0	2.0	8.0	1.0	2.0	1.0	2.0	3.0
6	3.0	3.0	1.0	3.0	2.0	2.0	1.0	3.0	1.0	3.0	1.0	22.0	3.0	3.0	1.0	2.0	3.0
7	2.0	3.0	3.0	3.0	5.0	3.0	5.0	3.0	2.0	3.0	3.0	21.0	3.0	2.0	2.0	3.0	1.0
8	3.0	3.0	3.0	3.0	5.0	4.0	4.0	3.0	2.0	2.0	3.0	0.0	0.0	2.0	1.0	3.0	2.0
9	3.0	1.0	1.0	1.0	1.0	1.0	1.0	3.0	1.0	3.0	1.0	20.0	3.0	2.0	1.0	2.0	1.0
10	1.0	2.0	3.0	2.0	5.0	3.0	4.0	1.0	2.0	3.0	3.0	9.0	2.0	2.0	0.0	1.0	1.0
11	3.0	2.0	4.0	2.0	5.0	3.0	6.0	3.0	2.0	1.0	3.0	7.0	1.0	2.0	1.0	2.0	1.0
12	2.0	1.0	1.0	2.0	1.0	1.0	2.0	2.0	1.0	1.0	1.0	5.0	1.0	1.0	1.0	2.0	1.0
13	1.0	1.0	0.0	2.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0
14	0.0	1.0	0.0	2.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0
15	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0
16	1.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	2.0	2.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0
17	2.0	1.0	4.0	1.0	1.0	1.0	1.0	2.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
18	3.0	2.0	3.0	2.0	5.0	2.0	5.0	2.0	2.0	1.0	3.0	10.0	2.0	1.0	0.0	1.0	1.0
19	3.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	17.0	3.0	1.0	0.0	1.0	2.0
20	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	2.0	3.0	2.0	19.0	3.0	1.0	1.0	1.0	2.0
21	2.0	1.0	1.0	1.0	4.0	2.0	2.0	1.0	2.0	2.0	3.0	13.0	2.0	1.0	1.0	1.0	1.0
22	2.0	0.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	6.0	1.0	0.0	0.0	1.0	1.0
23	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	8.0	1.0	1.0	1.0	1.0	1.0
24	1.0	1.0	1.0	1.0	1.0	2.0	2.0	1.0	1.0	1.0	2.0	9.0	2.0	1.0	0.0	1.0	1.0
25	2.0	1.0	1.0	2.0	3.0	2.0	3.0	2.0	2.0	2.0	3.0	11.0	2.0	2.0	1.0	1.0	1.0
26	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	5.0	1.0	0.0	1.0	1.0	1.0

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
SCENARIO A																	
1	3.0	2.0	2.0	2.0	3.0	2.0	3.0	3.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
2	1.0	2.0	3.0	3.0	1.0	3.0	1.0	3.0	2.0	3.0	2.0	2.0	0.0	1.0	3.0	2.0	3.0
3	3.0	1.0	1.0	1.0	3.0	3.0	3.0	3.0	0.0	2.0	0.0	0.0	2.0	2.0	3.0	1.0	3.0
4	0.0	2.0	2.0	2.0	0.0	3.0	0.0	3.0	2.0	3.0	3.0	2.0	0.0	0.0	0.0	2.0	3.0
5	3.0	2.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	1.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
6	3.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	2.0	3.0	3.0	2.0	1.0	3.0	3.0	3.0	3.0
7	1.0	2.0	3.0	3.0	2.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	3.0	3.0	2.0	3.0
8	3.0	2.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	2.0	1.0	1.0	0.0	1.0	3.0	1.0	3.0
9	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	3.0	3.0	2.0	2.0	2.0	0.0	2.0	2.0
10	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	1.0	0.0	0.0	2.0	1.0	0.0
11	0.0	3.0	3.0	2.0	4.0	3.0	0.0	3.0	1.0	1.0	1.0	2.0	2.0	2.0	0.0	2.0	3.0
12	3.0	1.0	1.0	2.0	2.0	1.0	3.0	1.0	2.0	0.0	3.0	1.0	1.0	0.0	2.0	1.0	1.0
13	0.0	2.0	2.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0
14	0.0	1.0	0.0	2.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	2.0	0.0
15	0.0	2.0	2.0	2.0	3.0	0.0	2.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0	2.0	0.0	0.0
16	3.0	3.0	2.0	2.0	2.0	0.0	3.0	3.0	2.0	0.0	0.0	2.0	0.0	2.0	1.0	2.0	0.0
17	1.0	2.0	0.0	1.0	3.0	0.0	0.0	1.0	2.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0	0.0
18	3.0	2.0	2.0	2.0	1.0	3.0	3.0	3.0	2.0	0.0	3.0	2.0	1.0	2.0	3.0	2.0	3.0
19	0.0	2.0	1.0	1.0	3.0	3.0	1.0	3.0	2.0	3.0	2.0	0.0	2.0	1.0	0.0	0.0	3.0
20	3.0	0.0	2.0	2.0	1.0	3.0	3.0	3.0	0.0	3.0	3.0	2.0	0.0	2.0	2.0	2.0	3.0
21	0.0	2.0	1.0	2.0	3.0	3.0	2.0	3.0	2.0	1.0	0.0	2.0	2.0	1.0	2.0	2.0	3.0
22	3.0	0.0	2.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	3.0	0.0	0.0	2.0	0.0	0.0	2.0
23	0.0	2.0	0.0	2.0	3.0	2.0	0.0	3.0	2.0	0.0	0.0	2.0	2.0	0.0	2.0	2.0	0.0
24	3.0	0.0	2.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	3.0	0.0	0.0	2.0	0.0	0.0	2.0
25	0.0	2.0	1.0	2.0	3.0	3.0	1.0	3.0	2.0	3.0	0.0	2.0	2.0	0.0	2.0	2.0	1.0
26	3.0	0.0	2.0	2.0	2.0	1.0	3.0	1.0	1.0	1.0	3.0	1.0	1.0	2.0	1.0	2.0	0.0
SCENARIO I																	
1	3.0	2.0	2.0	2.0	3.0	2.0	3.0	3.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
2	2.0	2.0	2.0	2.0	0.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
3	3.0	2.0	2.0	2.0	3.0	3.0	0.0	0.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
4	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0	3.0
5	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
6	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
7	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0	3.0
8	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	1.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
9	3.0	2.0	2.0	2.0	3.0	0.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0	3.0
10	3.0	2.0	2.0	2.0	0.0	3.0	3.0	3.0	2.0	0.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
11	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	0.0	2.0	2.0	2.0	2.0	2.0	0.0
12	0.0	2.0	2.0	2.0	3.0	0.0	0.0	0.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0
13	0.0	2.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0
14	0.0	0.0	2.0	0.0	3.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0
15	0.0	2.0	0.0	2.0	0.0	0.0	3.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0	2.0	2.0	0.0
16	3.0	2.0	2.0	2.0	3.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0	2.0	2.0	2.0	2.0	0.0
17	0.0	2.0	2.0	2.0	1.0	0.0	3.0	3.0	2.0	0.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0
18	3.0	2.0	2.0	2.0	3.0	3.0	3.0	0.0	2.0	0.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
19	3.0	2.0	2.0	2.0	0.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
20	3.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
21	3.0	2.0	2.0	2.0	3.0	3.0	0.0	3.0	2.0	0.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
22	3.0	2.0	2.0	2.0	0.0	0.0	3.0	3.0	2.0	0.0	0.0	2.0	2.0	2.0	2.0	2.0	0.0
23	3.0	2.0	2.0	2.0	3.0	2.0	0.0	0.0	2.0	0.0	3.0	2.0	0.0	2.0	2.0	2.0	0.0
24	0.0	2.0	2.0	2.0	0.0	0.0	3.0	3.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0
25	3.0	2.0	0.0	2.0	3.0	3.0	0.0	0.0	2.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	3.0
26	0.0	2.0	2.0	0.0	0.0	0.0	3.0	2.0	2.0	0.0	0.0	2.0	2.0	2.0	2.0	2.0	0.0

*Units in mm

C.3.Kharif 2015 Schedules

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
									PID								
1	1.0	1.0	1.0	0.0	1.0	1.0	3.0	0.0	2.0	1.0	1.0	2.0	2.0	0.0	0.0	1.0	0.0
2	3.0	2.0	1.0	0.0	1.0	2.0	5.0	1.0	2.0	2.0	4.0	2.0	2.0	1.0	1.0	1.0	1.0
3	3.0	2.0	1.0	1.0	1.0	2.0	3.0	3.0	1.0	2.0	3.0	2.0	1.0	1.0	0.0	0.0	1.0
4	3.0	2.0	1.0	1.0	1.0	1.0	5.0	2.0	2.0	3.0	1.0	2.0	2.0	2.0	1.0	0.0	1.0
5	2.0	2.0	1.0	0.0	4.0	4.0	4.0	1.0	2.0	3.0	4.0	2.0	2.0	1.0	1.0	0.0	1.0
6	3.0	2.0	2.0	1.0	3.0	4.0	5.0	3.0	1.0	1.0	4.0	2.0	1.0	2.0	1.0	1.0	2.0
7	3.0	2.0	1.0	2.0	1.0	1.0	1.0	4.0	1.0	3.0	1.0	1.0	2.0	3.0	1.0	1.0	3.0
8	2.0	3.0	2.0	2.0	4.0	3.0	7.0	3.0	1.0	3.0	3.0	2.0	3.0	3.0	1.0	1.0	2.0
9	3.0	3.0	3.0	1.0	4.0	3.0	7.0	3.0	2.0	2.0	4.0	3.0	2.0	4.0	2.0	0.0	2.0
10	3.0	3.0	2.0	1.0	3.0	2.0	4.0	3.0	1.0	3.0	2.0	2.0	2.0	4.0	2.0	0.0	3.0
11	2.0	3.0	2.0	1.0	2.0	2.0	3.0	3.0	2.0	4.0	2.0	2.0	3.0	4.0	1.0	1.0	2.0
12	1.0	3.0	3.0	2.0	3.0	3.0	6.0	2.0	3.0	3.0	3.0	3.0	3.0	4.0	3.0	2.0	1.0
13	2.0	1.0	3.0	1.0	3.0	2.0	3.0	2.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0
14	3.0	1.0	2.0	1.0	1.0	2.0	1.0	3.0	1.0	2.0	1.0	1.0	2.0	2.0	1.0	1.0	1.0
15	1.0	2.0	3.0	1.0	3.0	2.0	5.0	2.0	2.0	3.0	3.0	3.0	3.0	3.0	2.0	1.0	1.0
16	2.0	1.0	2.0	1.0	1.0	3.0	1.0	2.0	2.0	2.0	3.0	1.0	2.0	1.0	2.0	1.0	1.0
17	1.0	1.0	2.0	0.0	2.0	1.0	1.0	2.0	2.0	1.0	0.0	1.0	2.0	1.0	1.0	0.0	1.0
18	2.0	1.0	2.0	1.0	1.0	3.0	2.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0	1.0	1.0	1.0
19	2.0	2.0	2.0	1.0	1.0	2.0	4.0	2.0	2.0	2.0	3.0	2.0	4.0	2.0	2.0	1.0	2.0
20	3.0	3.0	3.0	1.0	2.0	1.0	6.0	3.0	2.0	1.0	3.0	3.0	2.0	3.0	2.0	1.0	2.0
21	3.0	3.0	1.0	2.0	1.0	1.0	7.0	3.0	2.0	4.0	0.0	2.0	3.0	3.0	0.0	2.0	2.0
22	1.0	1.0	3.0	1.0	3.0	3.0	4.0	1.0	1.0	2.0	3.0	3.0	2.0	3.0	2.0	1.0	2.0
23	2.0	2.0	3.0	1.0	2.0	3.0	6.0	3.0	2.0	2.0	2.0	3.0	2.0	3.0	3.0	1.0	2.0
24	2.0	2.0	3.0	1.0	1.0	1.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0	2.0
25	1.0	1.0	2.0	1.0	1.0	2.0	2.0	1.0	1.0	3.0	2.0	2.0	2.0	2.0	2.0	1.0	1.0
26	2.0	2.0	2.0	1.0	1.0	3.0	5.0	2.0	1.0	2.0	3.0	3.0	2.0	2.0	3.0	1.0	2.0

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
									SCENARIO A								
1	3.0	2.0	2.0	2.0	3.0	0.0	3.0	0.0	2.0	0.0	3.0	2.0	0.0	2.0	2.0	2.0	0.0
2	0.0	1.0	1.0	1.0	1.0	3.0	1.0	3.0	1.0	3.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0
3	3.0	2.0	2.0	2.0	3.0	1.0	3.0	2.0	2.0	1.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
4	0.0	2.0	1.0	1.0	1.0	3.0	1.0	3.0	0.0	3.0	3.0	1.0	0.0	1.0	0.0	1.0	1.0
5	3.0	2.0	2.0	2.0	3.0	0.0	3.0	3.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
6	0.0	2.0	0.0	1.0	2.0	3.0	0.0	3.0	0.0	3.0	2.0	0.0	0.0	0.0	2.0	1.0	3.0
7	3.0	2.0	2.0	2.0	3.0	3.0	3.0	1.0	2.0	1.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
8	3.0	1.0	1.0	1.0	1.0	3.0	1.0	3.0	0.0	3.0	3.0	2.0	0.0	1.0	3.0	1.0	3.0
9	1.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	2.0	1.0	1.0	2.0	2.0	3.0	2.0	3.0
10	3.0	1.0	1.0	1.0	1.0	3.0	1.0	3.0	1.0	2.0	3.0	2.0	0.0	1.0	3.0	0.0	3.0
11	0.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	3.0	0.0	0.0	2.0	2.0	0.0	2.0	3.0
12	3.0	1.0	1.0	1.0	1.0	3.0	1.0	3.0	1.0	2.0	3.0	2.0	1.0	1.0	2.0	0.0	3.0
13	1.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	2.0	1.0	2.0	2.0	2.0	1.0	2.0	1.0
14	3.0	1.0	1.0	2.0	1.0	0.0	3.0	1.0	0.0	3.0	3.0	1.0	0.0	2.0	2.0	1.0	3.0
15	0.0	2.0	2.0	0.0	3.0	3.0	0.0	3.0	2.0	3.0	3.0	2.0	2.0	0.0	0.0	2.0	0.0
16	3.0	0.0	0.0	2.0	1.0	3.0	3.0	3.0	1.0	2.0	0.0	1.0	0.0	2.0	2.0	1.0	3.0
17	0.0	2.0	2.0	0.0	3.0	0.0	0.0	0.0	2.0	0.0	3.0	2.0	2.0	0.0	0.0	2.0	1.0
18	3.0	1.0	1.0	2.0	1.0	3.0	3.0	3.0	1.0	0.0	1.0	1.0	1.0	2.0	2.0	1.0	3.0
19	0.0	2.0	2.0	0.0	3.0	3.0	0.0	0.0	2.0	3.0	3.0	2.0	2.0	0.0	0.0	2.0	2.0
20	3.0	2.0	3.0	2.0	1.0	3.0	3.0	3.0	2.0	0.0	3.0	2.0	0.0	2.0	2.0	1.0	3.0
21	0.0	2.0	0.0	0.0	3.0	3.0	0.0	3.0	0.0	3.0	0.0	0.0	2.0	0.0	0.0	2.0	3.0
22	3.0	1.0	2.0	2.0	1.0	0.0	3.0	2.0	2.0	2.0	3.0	2.0	0.0	2.0	2.0	0.0	3.0
23	1.0	2.0	1.0	0.0	3.0	3.0	0.0	3.0	1.0	3.0	1.0	1.0	2.0	0.0	3.0	2.0	3.0
24	3.0	1.0	2.0	2.0	1.0	3.0	3.0	0.0	2.0	1.0	3.0	2.0	0.0	2.0	3.0	1.0	3.0
25	1.0	2.0	3.0	1.0	3.0	1.0	0.0	3.0	1.0	3.0	1.0	0.0	2.0	0.0	1.0	2.0	3.0
26	3.0	3.0	3.0	2.0	2.0	3.0	3.0	3.0	2.0	1.0	3.0	2.0	3.0	2.0	2.0	3.0	3.0
									SCENARIO I								
1	3.0	2.0	2.0	2.0	3.0	0.0	3.0	0.0	2.0	0.0	3.0	2.0	0.0	2.0	2.0	2.0	0.0
2	1.0	2.0	2.0	2.0	1.0	3.0	3.0	3.0	2.0	0.0	0.0	2.0	2.0	2.0	0.0	2.0	3.0
3	3.0	2.0	2.0	2.0	3.0	0.0	0.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	0.0

Week No	1L-Disty	1R-Disty	2L-Disty	2R-Disty	3L-Disty	3R-Disty	4L-Disty	4R-Disty	5R-Disty	6R-Disty	7R-Disty	8R-Disty	9-R Disty	BS Disty	FC Disty	HL Disty	HR Disty
4	2.0	2.0	0.0	2.0	3.0	3.0	3.0	2.0	2.0	0.0	0.0	2.0	2.0	2.0	2.0	2.0	3.0
5	3.0	2.0	2.0	2.0	0.0	2.0	3.0	0.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
6	0.0	2.0	2.0	2.0	3.0	3.0	0.0	3.0	2.0	3.0	0.0	2.0	2.0	2.0	2.0	2.0	3.0
7	3.0	2.0	2.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	0.0
8	3.0	2.0	2.0	0.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
9	3.0	2.0	2.0	2.0	0.0	2.0	3.0	3.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
10	3.0	2.0	2.0	2.0	3.0	2.0	1.0	2.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
11	3.0	2.0	2.0	2.0	0.0	2.0	3.0	0.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
12	0.0	2.0	2.0	2.0	3.0	2.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	0.0	2.0	3.0
13	3.0	2.0	2.0	2.0	3.0	0.0	0.0	3.0	2.0	0.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
14	3.0	2.0	0.0	2.0	0.0	3.0	3.0	2.0	2.0	3.0	0.0	2.0	2.0	2.0	2.0	2.0	0.0
15	3.0	2.0	2.0	2.0	3.0	3.0	3.0	2.0	2.0	0.0	3.0	2.0	2.0	0.0	2.0	2.0	3.0
16	3.0	2.0	2.0	2.0	3.0	0.0	3.0	0.0	2.0	3.0	3.0	2.0	0.0	2.0	2.0	2.0	3.0
17	0.0	2.0	2.0	2.0	0.0	2.0	0.0	2.0	2.0	0.0	0.0	2.0	2.0	2.0	0.0	0.0	0.0
18	3.0	0.0	0.0	0.0	3.0	0.0	3.0	0.0	2.0	2.0	3.0	0.0	0.0	2.0	2.0	2.0	2.0
19	0.0	2.0	2.0	2.0	0.0	3.0	3.0	3.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	3.0
20	3.0	2.0	2.0	2.0	3.0	3.0	0.0	3.0	2.0	0.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
21	3.0	2.0	2.0	2.0	3.0	3.0	3.0	0.0	2.0	3.0	3.0	2.0	2.0	0.0	0.0	2.0	2.0
22	3.0	2.0	2.0	2.0	0.0	2.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0
23	3.0	2.0	2.0	2.0	3.0	0.0	0.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0
24	0.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	2.0	0.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0
25	3.0	2.0	2.0	2.0	4.0	3.0	3.0	0.0	2.0	3.0	3.0	2.0	3.0	2.0	2.0	2.0	0.0
26	3.0	2.0	2.0	2.0	0.0	0.0	3.0	3.0	2.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	3.0

*Units in mm